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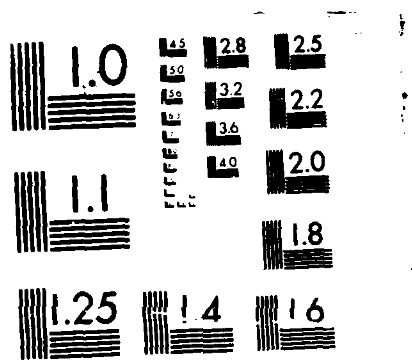

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COMPARATIVE EFFECTS ON TROUT HABITAT OF HYDROPOWER MODIFICATION WITH AND WITHOUT REREGULATION IN THE CUMBERLAND RIVER BELOW WOLF CREEK DAM, KENTUCKY

by

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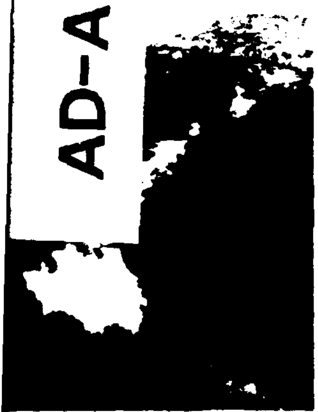

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The U. S. Army Engineer District, Nashville (ORN), regulates flows in the Cumberland River at Wolf Creek Dam to provide for hydropower generation and flood control. To meet future demands for power in the region, the ORN is considering optimizing the generating capability at Wolf Creek Dam by both uprating existing turbines and adding more generating capability. Reregulation of the increased releases from Wolf Creek Dam is under consideration to alleviate the flow fluctuations associated with the upgrade.

This report describes and quantifies the effects on trout habitat of hydropower modification and peaking operation at Wolf Creek Dam on trout habitat in the reach of the Cumberland River between Wolf Creek Dam and the site of the reregulation dam both with and without reregulation. The results of this comparison indicate that reregulation will generally have a beneficial impact on trout habitat, primarily because the backwater effects caused by the reregulation dam reduce the water velocities associated with peak discharge.

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PREFACE

This report was prepared by the Environmental Laboratory (EL), US Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss. The project was authorized by US Army Engineer District, Nashville, under Intra-Army Order for Reimbursable Services No. 85-0070, dated 2 April 1985 and amended 26 June 1985.

This report was written by Ms. L. Toni Curtis, Dr. John M. Nestler, and Dr. James L. Martin. This report was prepared under the direct supervision of Dr. Martin, EL, and under the general supervision of Mr. Mark S. Dortch, Chief, Water Quality Modeling Group (WQMG), EL; Mr. Donald L. Robey, Chief, Ecosystem Research and Simulation Division, EL; and Dr. John Harrison, Chief, EL. The in-house technical review was performed by Mr. Ross W. Hall and Dr. James A. Gore of the WQMG.

This report provides an evaluation of the effects on trout habitat of hydropower modification both with and without reregulation downstream of Wolf Creek Dam. Information provided in this report can be used to assess the effects of reregulation in conjunction with hydropower modification, to provide a partial basis for mitigation, and to provide information for designing and operating the proposed reregulation dam to protect trout habitat.

COL Allen F. Grum, USA, was the previous Director of WES. COL Dwayne G. Lee, CE, is the present Commander and Director. Dr. Robert W. Whalin is the Technical Director.

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CONTENTS

COMPARATIVE EFFECTS ON TROUT HABITAT OF HYDROPOWER MODIFICATION WITH AND WITHOUT REREGULATION IN THE CUMBERLAND RIVER BELOW WOLF CREEK, KENTUCKY

PART I: INTRODUCTION

Background

Nashville District (ORN) presently regulates flows in the Cumberland River at Wolf Creek Dam, located at river mile (RM) 460.9, to provide for hydropower production and flood control. Located in southeastern Kentucky, Wolf Creek Dam is an integral part of a coordinated system for flood protection in the Cumberland and Ohio river valleys, significantly reducing flood stages at Nashville, Tennessee, and contributing to flood damage reduction as far downstream as the lower Mississippi River. The dam is a combination earthfill and concrete structure 5,736 feet long and 258 feet high, with a gated spillway. Six hydroelectric generating units with a total capacity of 270,000 kilowatts were installed at Wolf Creek Dam and placed on line for power production between 1951 and 1952. The estimated average annual energy output of the existing Wolf Creek power plant is about 800,000,000 KWh.

To aid in meeting future power demands, modification of the hydropower generation capabilities is under consideration at Wolf Creek Dam. These modifications include the addition of new units, refitting or uprating of existing units, and a change from base load generation to peaking power generation. The project currently releases a daily average flow of 9,160 cfs with a maximum release of 40,000 cfs. Revised operating plans under consideration would increase flows to a maximum of 60,000 cfs.

The more extreme flow fluctuations from Wolf Creek Dam associated with hydropower modification may have a detrimental effect on the fishery and channel stability in the tailwater. The Cumberland River below Wolf Creek Dam currently supports a successful trout fishery. The State of Kentucky regularly stocks the river with rainbow trout and brown trout, and Corps personnel report that a good trout fishery exists below Wolf Creek Dam. Both reduced flows during nongeneration and increased flows during generation resulting from hydropower modification may limit fish habitat during some part of the generation cycle. In addition, the highly fluctuating flows associated with peaking operation may result in increased bank sloughing in the Cumberland River, further affecting fish habitat. To reduce these downstream effects of proposed hydropower modifications at Wolf Creek Dam, the ORN is considering the construction of a reregulation (rereg) dam downstream from Wolf Creek Dam. The rereg dam would reregulate the fluctuating flows from Wolf Creek Dam by releasing more constant flows, thereby improving fish habitat (Martin, Curtis, and Nestler 1985) and reducing the potential for bank sloughing. However, the extreme flow fluctuations associated with peaking hydropower operations under the modification would continue to affect the Cumberland River fishery in the pool of the reregulation dam.

Objective

Although flow fluctuations will be reduced downstream from the proposed rereg dam, the increased water level fluctuations within the pool of the rereg dam may have considerable impact on the fishery. Information is required to quantify the effects of reregulation between Wolf Creek Dam and the site of the proposed reregulation dam on fish habitat. This report quantifies the effects of

extreme flow fluctuations on fish habitat below Wolf Creek Dam under two projected operating plans- with and without reregulation. The results of this study will allow a comparison of fish habitat under future conditions of hydropower modification for both with and without reregulation. This information may aid in assessing the environmental impact of operation on fish habitat and establishment of operational guidelines for the future. The fish species' life stages targeted in this study include juvenile brown trout, adult brown trout, and adult rainbow trout.

PART II: METHODS AND MATERIALS

General Approach

An examination and evaluation of the issues related to the proposed Wolf Creek Dam hydropower optimization indicated that, with some modification, the Physical Habitat Simulation System (PHABSIM) developed by the Instream Flow Group, U. S. Fish and Wildlife Service, could be used as a tool to predict and manage fish habitat downstream in the Cumberland River below Wolf Creek Dam. PHABSIM was selected for the following reasons:

(a) It is generally accepted by many agencies as a defensible assessment method.

(b) The form of the results of an instream flow study using PHABSIM are amenable to incorporation in studies resolving potential water resources conflicts.

(c) It is incremental, that is, it relates small changes in operation to changes in habitat for target life stages.

(d) It is well-documented and supported.

(e) It is flexible; the organization of the system is such that changes can be made easily as the state-of-the-art of fish habitat simulation increases and additional studies provide more information to the analysis.

PHABSIM Description

Background

The PHABSIM system is based on the observation that most species of fish prefer certain combinations of depth, velocity, and cover and tend to avoid other combinations of these parameters. If the relative values of different depths and velocities for each species are known and the hydraulic conditions within the channel can be described for different discharges, then it becomes possible to determine both the quality and quantity of habitat for each species of fish at these different discharges. Thus, an instream flow study consists of three essential steps. The first part involves a description of the depth, velocity, and cover available in the river at discrete discharges. The second part is the development of criteria for each species of fish. The last part of an instream flow study is to combine parts one and two for each discharge of interest to derive an estimate of the value or worth of the river for each fish species at each discharge. The above discussion provides only a summary of the conceptual basis of the PHABSIM system. Depending upon the problem at hand, the user may choose any of a number of different options and approaches to complete an analysis. The next sections will detail how these general steps were applied to the Cumberland River.

Suitability Curves

Suitability (or criteria) curves must be identified or generated to relate cell-by-cell flow conditions in the study river reach to useability by a target life stage. That is, the value of conditions represented by cell(i) for a particular target species or life stage can be assessed if the criteria (the value of different velocities, depths, and substrates) are either known initially

or identifiable with further study. Curves of trout life stages are attached as Appendix A. Note that the range of potential values vary from zero (no value) to one (ideal conditions) for each variable.

The criteria values for each variable can be combined in several different ways to generate a single value of useability (a weighting factor) for the velocity, depth, and cover conditions in each cell. The most commonly used method (and the default option in PHABSIM) to generate this weighting factor is by multiplying the individual suitability values for each variable (velocity, depth, and substrate) together to generate a product. For example, if velocity, depth, and cover values in cell(i) are all optimum (that is, they all have values of one) then the resulting weighting factor for cell(i) is 1.0 times 1.0 times 1.0 or 1.0. Other options for combining suitabilities for depth, velocity, and substrate are available and if necessary the code of PHABSIM can be modified. For most applications of PHABSIM, depth, velocity, and cover are assumed to be independent variables, even though these variables are known to be correlated. If necessary, bivariate representations of depth and velocity can be used; however, field data must then be collected to develop bivariate suitability criteria since almost all published suitability curves present depth and velocity as independent variables. Additional information on different ways of combining individual suitability curves to generate a composite suitability or weighting value can be obtained in Milhous et al. 1984. Additional information on interpreting, evaluating, and generating suitability curves can be found in Bovee (1985).

Estimating Habitat

In a typical application of PHABSIM, the values for depth, velocity, and substrate in cell(i) are each evaluated relative to the criteria for the target life stage to generate a weighting factor for the surface area of river represented by cell(i)

$$W(i) = suit(d) \times suit(v) \times suit(c)$$

where

W(i) - weighting factor for cell(i)
suit(d) - suitability of the depth in cell(i) for a given discharge for the target life stage
suit(v) - suitability of the velocity in cell(i) for a given discharge for the target life stage
suit(c) - suitability of the cover in cell(i) for the target life stage

The amount of river area available for a target life stage in cell(i) can be represented as

$$WUA(i) = area(i) \times W(i)$$

where

WUA(i) - weighted useable area of the river surface area represented by cell(i)
area(i) - area of the river represented by cell(i)
W(i) - weighting factor for cell(i)

The total Weighted Useable Area (WUA) in the study reach available for use by the target life stage for a given discharge can then be represented as the sum of the weighted areas of each cell or

$$WUA(t) = \sum_{n}^{i=1} WUA(i)$$

where

WUA(t) - total WUA for a given life stage
WUA(i) - WUA in cell (i)

n - number of cells in the river reach of interest
E - summation symbol

This formulation allows estimation of a single habitat value that is a function of discharge for the target life stage. The habitat available at other discharges can then be calculated in a similar fashion to generate a habitat versus discharge relationship.

The above discussion presents only the most fundamental underpinnings of PHABSIM. Many other techniques, options, and programs are available that provide for complete analyses of water development projects including comparisons of different operational or structural alternatives, time series analysis, and other types of habitat analyses. The interested reader should consult Instream Flow Information Paper No. 11 (Milhous et al. 1984) and No. 12 (Bovee 1985) for more details on the use and application of PHABSIM.

Simulation Strategy

Background

The standard version of PHABSIM disseminated by the USFWS for relating fish habitat to reservoir project operation was considered inadequate for the Cumberland River application because it is restricted to steady-state or gradually varied flow applications. A fish habitat model that could simulate habitat conditions under highly dynamic flow conditions was required to accurately predict fish habitat conditions under peaking conditions.

Under dynamic flow conditions, the peak release associated with hydropower production attenuates and the base flow increases as the flows move downstream; thus, steady flow hydraulics are usually inadequate since the discharge at the

dam may not reflect conditions at points downstream of the dam. Additionally, hysteresis may occur as the stage rises and falls because of backwater effects.

The best method of hydraulic simulation within PHABSIM for constant flow conditions (described in Appendix L of Milhous et al 1984 - "Use of WSP and IFG-4 Together for Hydraulic Simulation") is described below followed by a discussion of how this method was modified to simulate fish habitat under dynamic flow conditions.

Habitat Simulation Under Steady-State Conditions

In the approach documented in Appendix L of Milhous et al. (1984) for steady flows, a step backwater hydraulic program, Water Surface Profile (WSP), is utilized to predict water surface elevations at different discharges for separate cross sections in a river reach for steady, non-uniform flows. The stage-discharge information calculated by the WSP program is then passed to the IFG-4 program. It should be noted that the output of HEC-2 or any other steady state hydraulic program commonly used by the CE, can be substituted for the WSP program to provide stage-discharge information necessary for a PHABSIM system analysis. Additionally, stage-discharge information can be obtained from a gage if a gage is available or measured in the field by establishing a gaging cross section in each study reach.

The IFG-4 program takes the stage-discharge information from the WSP program (or other source) and partitions the flow into a series of lateral cells at each cross section. Several options within the IFG-4 program are available to generate cell depths and velocities for a given stage and discharge. If no measured velocities are available, then the program separates the total discharge into cells based upon the hydraulic radius of each cell. For constant cell

widths this formulation results in deeper cells having greater water velocities. Flow patterns in cross sections located on bends or with complex channel morphology cannot be adequately described using hydraulic radius to partition out the total flow into cells. Alternatively, velocity measurements made in the field under a constant discharge can be used to calibrate the IFG-4 program. In the latter case, the known laterally varying velocities are used to solve Manning's equation for "Manning's n" for each lateral cell since all other variables are known. The calculated cell-specific "n" value is then used to generate depths and velocities in each cell at all simulated discharges. After estimating a lateral flow pattern, the IFG-4 program checks the calculated water surface elevation against the given water surface elevation provided by the WSP program and then, if necessary, modifies all cell velocities by a common factor to raise or lower the calculated water surface elevation until it matches the water surface elevation provided by the WSP program. Calibration of the IFG-4 program to measured velocities is generally superior to using hydraulic radius for estimating lateral flow patterns. However some caution must be exercised in the selection of the calibration flow. A lateral velocity pattern observed in a river at very low flows may not be accurate at high flows because of the increased influence of the bottom during very low flows. If field inspection of the cross section indicates a likely shift in flow pattern with discharge, then multiple velocity calibration data sets may be required.

Habitat Simulation Under Dynamic Flow Conditions

Conceptually, the Cumberland River application of PHABSIM under dynamic flow conditions was similar to the approach discussed above, except that the WSP model was replaced by a one-dimensional (riverine) dynamic flow model (Bedford, Sykes, Libicki 1982). It should be noted that the stage-discharge pairs provided by the dynamic flow model are time-varying. Thus, the final results of the analysis for one cross section are habitat as a function of time and not habitat as a function of discharge, as is usual in an instream flow study. Each time increment (for example - one hour) has associated with it a specific discharge. The hydraulic code and companion riverine water quality code together comprise a modeling system referred to as CE-QUAL-RIV1. This riverine flow code was selected for use because it can:

(a) Also be used to drive a water quality subroutine;

(b) Simulate highly unsteady flows;

(c) Simulate a stream network;

(d) Include instream hydraulic control structures.

The dynamic flow model is used to pass time varying stage/discharge information to the IFG-4 program of the PHABSIM system. No further modifications of PHABSIM were required once the stage-discharge information was passed to the IFG-4 program, although several supporting graphics programs were written specifically for the Cumberland River application. The unsteady flow code used in the application can be replaced by any other dynamic, one-dimensional riverine hydraulic code that can provide stage-discharge information to the IFG-4 program of the PHABSIM analysis.

Flow and Channel Description

Site Description

The river reach investigated in this study was bounded upstream by Wolf Creek Dam (RM 460.9) and downstream by the estimated location of the proposed rereg dam (RM 450.70). Channel cross sections used in this study were surveyed in April of 1985. These cross sections were initially used by ORN to perform the hydraulic simulation necessary to design the rereg dam and also to determine the elevation-capacity relationship for the rereg pool. Of the cross sections originally provided by ORN, twelve were selected for analysis. Cross sections selected for analysis were located at river miles 450.95, 451.20, 451.70, 452.76, 453.18, 454.70, 455.10, 455.90, 457.16, 457.40, 459.26, and 460.00. Cross sectional plots can be found in Appendix B.

The reach of the Cumberland River investigated in this study is generally representative of a large, upland river flowing through rugged terrain. The slope is moderate, approximately three feet per mile. Channel widths at a discharge of 4000 cfs vary from approximately 200 to 500 feet. Substrate was composed predominantly of rubble, cobble, and occasional boulders near the steeper banks with gravel predominating in the center of the channel. Sandy channel bottoms and banks occurred in the lower portion of the study reach.

Field Methods

Velocity Calibration Data. Cell-by-cell velocity information was required to develop the velocity calibration data set to predict the velocity pattern across each cross section (see "Habitat Simulation Under Steady-State Flow Conditions" for more details). Velocity information was collected on 21 August

1985 to 23 August 1985 by field crews composed of representatives of the WES, ORN, USFWS, and the commonwealth of Kentucky. The field crews relocated the previously surveyed cross sections by surveying from an established point (usually a head pin) following the field notes of the original survey party. Once the channel cross sections were relocated, channel coordinates were relocated using an 880 ft, .125 inch wire-cable tag line. The tag line was secured to the river bank, unreeled across the Cumberland River using a 16 ft jon boat, and tightened using a come-along. Each cross section was first surveyed using a Lowrance depth finder to provide a continuous record of the cross section and also to locate substantial changes in the channel bottom profile. The work boat was hand secured to each of the cross section coordinate points and a velocity measurement was made using a Marsh-McBirney current meter. The reading was noted after the meter reading had stabilized. Velocity measurements were initially made at .2 and .8 depths; however, because of time constraints, most velocity measurements were made at .6 depth. Discharge from Wolf Creek Dam was approximately 4000 cfs during most of the resurvey.

When possible, the coordinate points from the original survey were relocated for velocity measurements. However, for several cross sections discrepancies in the field notes of the original survey could not be reconciled in the field and the original coordinate points could not be relocated. For these cross sections, new coordinate points were established at approximately 15 ft intervals or whenever the channel bottom profile changed.

Cover Code. The criteria for trout species and lifestages used in this study were based upon previous studies on the Chattahoochee River, North Georgia (Nestler et al. 1985). The proximity of the Chattahoochee and Cumberland Rivers and similarities between them suggest that the suitability curves developed for

the Chattahoochee River study should be applicable to the Cumberland River. Descriptions of the cover codes can be found in Table 1.

Selection of Simulation Time Period

Simulation of habitat under dynamic flow conditions is complicated by the diversity of flow conditions experienced by fish temporally and spatially. That is, flow conditions change daily and seasonally because of the varying discharges from Wolf Creek Dam and thus can confound comparisons of design or operation alternatives.

Weeklong, representative time-varying discharges for a typical July operating schedule associated with both nonreregulation and reregulation flow conditions were provided by the ORN to the WES. However, limitations in the PHABSIM system software precluded evaluating each weeklong release schedule in its entireity. However, examination of hydrographs for the two flow alternatives indicated that 2:00 P.M. Thursday (hr 38 - based on one week of generation - 0 hr is 12:00 P.M. Tuesday-168 hr is 12:00 P.M. Tuesday of the following week) through 2:00 P.M. Friday (hr 62) was representative of weekday generation and 4:00 P.M. Sunday (hr 112) through 4:00 P.M. Monday (hr 136) was representative of weekend operation. During these time periods, the discharges at Wolf Creek Dam ranged from 500 cfs to 48,000 cfs. A minimum of 500 cfs was released from Wolf Creek Dam during nongeneration periods to prevent mathematical instabilities from the hydraulic module. The worst flow conditions for trout habitat is not low flow coniditons, but zero flow conditions. Since the hydraulic model cannot handle zero flows, a minimum release of 500 cfs was the closest condition to the critical zero flow that ORN is capable of simulating.

Table 1

Channel Index for Trout Used for the Cumberland River

Channel Index	Suitability	Description
1.0	0.10	all sand - no cover
1.5	0.15	gravel - no cover
2.5	0.25	sand - some cover
3.0	0.30	sand - extensive cover
4.0	0.40	gravel - extensive cover
5.0	0.50	cobble (75-254 mm) - some cover
6.0	0.60	boulder - some cover
7.0	0.70	bedrock - some cover
8.0	0.80	cobble - extensive cover
9.0	0.90	bedrock - extensive cover
10.0	1.00	boulder - extensive cover
11.0	0.50	upland vegetation

Model Implementation

Implementing both the unsteady flow code and the PHABSIM system requires a number of data manipulations, preliminary analyses, and generation of a number of different model coefficients and exponents. The following discussion in this section describes the implementation of both the CE-QUAL-RIV1 code and the PHABSIM system.

The reach for hydraulic simulations consisted of 25 cross sections extending from RM 460.9 (Wolf Creek Dam) to RM 444.5 (downstream boundary) and encompassing the site of the rereg dam RM 450.7. Hydraulic simulations were conducted for a week representing a typical July operating schedule. A total of 12 of the 25 cross sections and two of the seven days were selected for PHABSIM simulation.

CE-QUAL-RIV1 Implementation

The following discussion describes the steps necessary to implement the CE-QUAL-RIV1 dynamic flow model. Activities to implement CE-QUAL-RIV1 can be generally categorized as:

(a) Efforts to develop separate coefficients for each cross section for an equation that relates elevation to cross-sectional area;

(b) Generate boundary conditions and initial conditions;

(c) Model calibration.

CE-QUAL-RIV1 does not use actual tabulated cross-sectional area but rather calculates cross sectional area from stage information using

```
A=C1*H + C2*(H**C3)
```

where

A - cross sectional area
H - depth
C1 - coefficient that represents bottom width

C2 - coefficient that represents side slope
C3 - coefficient that represents curvature of channel

The depth/cross-sectional area information necessary to estimate the coefficients was obtained using the Geometric Elements From Cross Section Coordinates (GEDA) program (Hydrologic Engineering Center 1976). The channel coordinate information was input into GEDA and outputted as tables of cumulative cross-sectional area as a function of elevation separately for each cross section. Separate coefficients for each cross section were estimated using the Nonlinear Regression Procedure of SAS (SAS Institute Inc. 1984) to analyze the depth/cross-sectional area information in the tables output by GEDA.

CE-QUAL-RIV1 requires boundary conditions at the upstream and downstream cross sections of the river reach being simulated. Upstream boundary conditions can be formulated as either constant (steady state) or variable dynamic discharge or head. Downstream boundary conditions can be simulated as steady or dynamic, head or discharge or as a stage-discharge relationship. Discharges (the downstream boundary condition) for the reregulation dam were provided by the ORN.

A discharge rating curve

Q=A*(H**B)

where

Q - discharge
H - stage
A - coefficient
B - coefficient

was used to describe the stage-discharge relationship for the downstream boundary condition at RM 444.5. Coefficients for the discharge rating curve were estimated using the Nonlinear Regression Procedure of the Statistical Analysis

System (SAS Institute, Inc. 1984). Stage-discharge pairs used in the regression model were provided by ORN.

The coefficients C1, C2, and C3 for each cross section derived from the nonlinear regression of the depth/area tables, inflows from Wolf Creek Dam, outflows from the rereg dam, initial conditions, "Manning's n" values, and coefficients for the downstream boundary condition were used as input for CE-QUAL-RIV1.

Simulations with RIV1H for the 168 hour period were conducted using a time step of 200 seconds. Simulations were conducted for conditions with and without reregulation.

Measured data were unavailable for model calibration. Comparisons were made between the predictions of CE-QUAL-RIV1 and the results of applications of the unsteady flow model BIRM (Johnson 1983) by the ORN. The model results were generally similar, although notable discrepancies in predicted maximum water surface elevation with reregulation did occur. The reasons for these discrepancies are not as yet known.

PHABSIM Implementation

Implementing PHABSIM, required the execution of two models - IFG-4 and HABTAT. The necessary information for an IFG-4 input data set included distance-elevation coordinate pairs, cover codes, stage-discharge pairs, and velocity calibration values for each cross section. Channel geometry information necessary to complete the input data sets for the IFG-4 program was provided by ORN or collected in the field. Velocity information was collected by representatives of WES, ORN, USFWS, and the commonwealth of Kentucky (see Field

Methods for more details). The stage-discharge pairs were provided by the output of RIV1H. A separate input data set was generated for each cross section.

CE-QUAL-RIV1--PHABSIM Linkage

The CE-QUAL-RIV1 model and PHABSIM system, when coupled together, can be used to determine the effects of peaking operation on tailwater habitat. RIV1H, the hydraulic code of CE-QUAL-RIV1, was executed to create stage-discharge pairs needed for IFG-4. The IFG-4 program then generates a distribution of velocities and depths across the cross section, one distribution for each stage-discharge pair at a preselected interval (which in present model formulation represent hourly stage and discharge updates). After predicting the velocity and depth distributions across a cross section, the IFG-4 program passes this information to the HABTAT program in which the cell by cell conditions are evaluated relative to the criteria of the target life species. The result of HABTAT is the amount of available weighted useable area for each targeted species for each specific discharge.

PART III: RESULTS

Interpretation of Results

The results of PHABSIM analyses are ordinarily presented in terms of "weighted useable area" (WUA) per specified length of river (1000 feet in this application). WUA is defined as the surface area of river available as habitat for a target fish species. See "Estimating Habitat" for an explanation of how PHABSIM calculates habitat.

The results of this analysis are presented both by individual cross sections as WUA over time and also summarized as both average and minimum habitat for each cross section for the entire reach. Presentation of the results by individual cross sections provides a more detailed depiction of trout habitat changes under dynamic flow conditions. Under dynamic flow conditions, discharge can vary throughout the reach as the power wave attenuates and the base flow increases as the releases move downstream. Thus, reach summaries may not provide a complete description of the effects of generation since habitat at any one cross section may vary from zero to optimum over a generation cycle.

Results in this report are presented in terms of WUA per 1000 feet of stream. This representation allows direct comparison of cross sections, even if the length of river that each represents varies, and also allows an accurate depiction of the habitat effects due to dynamic flows at each cross section. Plots of the resulting habitat changes for individual cross sections can be found in Appendix C. Note that the axes are different from the habitat-discharge plots

ordinarily generated by an instream flow study. In this case, the axes are habitat as a function of time with each point on the ordinate representing the habitat available at the cross section for the flow conditions at that time. For the sake of clarity and brevity, plots for individual cross sections are not discussed in the text. Instead, only three-dimensional plots are presented and discussed in the next section. If necessary, the individual cross sections can be examined in Appendix C if more detailed information is required.

WUA values presented in the results can be proportionally related to channel width by dividing by 1000 and then dividing by channel width. For example, if WUA is 200,000 then the proportion of river area available is 200,000 divided by 1000 divided by 400 (approximate channel width). Thus, approximately half of the river channel is available for habitat for the example given above.

Results are also presented in summary form by multiplying the length of river that each cross section represents (the reach multiplier) by the WUA per 1000 feet (see Tables 2 and 3). Habitat values represented by each cross section are then summed to generate a total reach summary. Summary results are presented for both total habitat and minimum habitat available for each target species. The reader must be aware though that considerable detail is lost in the course of summarizing the effects of dynamic flow conditions. For further information concerning the relationship between river surface area and suitability calculations, the reader is referred to Bovee (1985).

Relative Flow Conditions

Changes in habitat in the reach of the Cumberland River between Wolf Creek Dam and the site of the proposed reregulation dam are primarily determined by flow conditions. Plots of stage and discharge versus time for all study conditions are provided in Appendix D. Under nonreregulated conditions during weekday operation (38 hours to 62 hours), discharges from Wolf Creek Dam (RM 460.9) ranged from 500 cfs to 48,000 cfs. Water surface elevation at RM 460.00 varied from 544.5 to 563.5 ft. Discharges at RM 450.95 (approximately .2 mile upstream from the site of the reregulation dam) ranged from 28,000 cfs to 2,000 cfs as the power wave released from the dam attenuated and the base flow increased. Water surface elevations at RM 450.95 varied from 536 ft. to 552.5. During weekend operation (112 hours to 136 hours), flows from Wolf Creek Dam ranged from 500 cfs to 24,000 cfs. Water surface elevations at RM 460.00 varied from 544.5 to 556.0. Discharges at RM 450.95 ranged from 2,000 to 11,000 cfs and water surface elevations varied from 538 ft to 545 ft. Note the substantial decrease in both maximum water surface elevation and maximum discharge from weekday to weekend generation and the decrease in amplitude of both water surface elevations and discharge from upstream to downstream cross sections.

Under reregulation conditions during weekday operation, discharges from Wolf Creek Dam ranged from near 0 to 48,000 cfs and water surface elevation varied from 545.5 to 563.5 ft. Discharges at RM 450.95 ranged from 6,000 to 8,000 cfs and water surface elevation varied from 543 to 563 ft. During weekend operation flows from Wolf Creek Dam again ranged from 500 cfs to 24,000 cfs and water surface elevation varied from 545.5 to 556.5. Discharges at RM 450.95 ranged from 3,000 cfs to 4,000 cfs and stage varied from 544 ft. to 553 ft.

Although discharge from Wolf Creek Dam does not change between reregulated and nonreregulated conditions, minimum water surface elevation (Appendix D - Compare same river mile under reregulation and nonreregulation conditions) differs as does the rate of change in water surface elevation over a generation cycle. Thus, backwater effects caused by the reregulation dam results in less fluctuation in both stage and discharge within the pool of the reregulation dam.

Hydropower Modification Without Reregulation

General Results

The general results for adult brown trout and rainbow trout are very similar under nonreregulation conditions. In most cases, habitat for each species was at a minimum during high flows from Wolf Creek Dam and at a maximum during low and intermediate flow periods. Juvenile brown trout exhibited the least amount of habitat in this river reach.

Brown Trout

Habitat for adult brown trout under nonreregulation varies both by distance and over time. In general, suitable habitat appears to decrease with increasing distance from Wolf Creek Dam (Figures 1 and 2).

Habitat changes substantially as discharges vary over a generation cycle. Habitat is minimal, often approaching zero for some cross sections during maximum releases from Wolf Creek Dam (Figures 1 and 2). Minimum WUA's by cross section are provided in Table 2 and Figures 3 and 4. Average habitat values for each cross section, calculated as the mean of the 24 one-hour habitat values, are also low ranging from 32,000 to 134,000 sq. ft. of WUA with most values varying from 32,000 to 60,000 sq. ft. of WUA (Table 3, Figures 5 and 6).

Table 2

Minimum WUA Per 1000 Feet of Stream by Cross Section, Minimum WUA for the River Represented by Each Cross Section and Total Minimum WUA for Adult Rainbow Trout and Adult Brown Trout

FLOW CONDITION	RIVER MILE	RAINBOW TR. WUA 1000 FT	BROWN TR. WUA 1000 FT	REACH MULTI-PLIER	RAINBOW TR. WUA C/S TOTAL	BROWN TR. WUA C/S TOTAL
WEEKDAY REREGULATION	450.95	40224	48765	2.482	99835	121035
	451.20	14850	20479	1.980	29404	40548
	451.70	24816	31948	4.118	102194	131560
	452.76	14909	16639	3.907	58248	65007
	453.18	22657	28323	5.122	116047	145072
	454.70	14562	19948	5.069	73815	101117
	455.10	17057	23573	3.168	54036	74680
	455.90	7827	17865	5.438	42561	97152
	457.16	7946	12555	3.960	31464	49718
	457.40	4338	17757	5.544	24051	98444
	459.26	17431	64089	6.864	119643	439904
	460.00	22279	28758	6.706	149404	192851
	TOTAL OF CROSS SECTION MINIMUMS				900703	1557088
WEEKEND REREGULATION	450.95	54773	87462	2.482	135947	217082
	451.20	47495	51926	1.980	94039	102813
	451.70	38822	87477	4.188	159870	360231
	452.76	7054	41886	3.907	27560	163649
	453.18	18016	45445	5.122	92279	232770
	454.70	25071	31013	5.069	127083	157205
	455.10	20271	26832	3.168	64219	85005
	455.90	21114	24029	5.438	114819	130672
	457.16	20365	16773	3.960	80647	66421
	457.40	5467	19562	5.544	30307	108453
	459.26	18605	63137	6.864	127703	433373
	460.00	11645	25740	6.706	78092	172613
	TOTAL OF CROSS SECTION MINIMUMS				1132566	2230285

(continued)

NOTE: Reach multiplier is the length of river represented by each cross section. To obtain minimum WUA for the reach of river represented by each cross section, multiply the WUA per 1000 ft times the reach multiplier.

Table 2 (concluded)

FLOW CONDITION	RIVER MILE	RAINBOW TR. WUA 1000 FT	BROWN TR. WUA 1000 FT	REACH MULTI-PLIER	RAINBOW TR. WUA C/S TOTAL	BROWN TR. WUA C/S TOTAL
WEEKDAY NONREREGULATION	450.95	28876	42622	2.482	71671	105788
	451.20	14157	22749	1.980	28031	45044
	451.70	23981	25480	4.118	98755	104928
	452.76	10258	12285	3.907	40079	47999
	453.18	12177	23025	5.122	62369	117933
	454.70	9180	15847	5.069	46534	80327
	455.10	16905	23918	3.168	53555	75772
	455.90	6979	8832	5.438	37952	48029
	457.16	7551	10575	3.960	29900	41876
	457.40	3578	9868	5.544	19834	54709
	459.26	29336	62181	6.864	201359	426812
	460.00	21476	28186	6.706	144018	189016
	TOTAL OF CROSS SECTION MINIMUMS				834057	1338233
WEEKEND NONREREGULATION	450.95	35922	45818	2.482	89158	113721
	451.20	15875	22296	1.980	31433	44146
	451.70	24885	32847	4.118	102478	135264
	452.76	10521	13893	3.907	41104	54281
	453.18	13089	23136	5.122	67041	118502
	454.70	9116	15779	5.069	46207	79985
	455.10	18342	25031	3.168	58109	79299
	455.90	13561	17750	5.438	73742	96525
	457.16	17540	15052	3.960	69460	59605
	457.40	3573	9797	5.544	19811	54315
	459.26	28175	61284	6.864	193393	420654
	460.00	17693	24952	6.706	118651	167325
	TOTAL OF CROSS SECTION MINIMUMS				910587	1423621

Table 3

Average WUA Per 1000 Feet of Stream by Cross Section, Average WUA for the River Represented by Each Cross Section and Total Average WUA for Adult Rainbow Trout and Adult Brown Trout

FLOW CONDITION	RIVER MILE	RAINBOW TR. WUA 1000 FT	BROWN TR. WUA 1000 FT	REACH MULTI-PLIER	RAINBOW TR. WUA C/S TOTAL	BROWN TR. WUA C/S TOTAL
WEEKDAY REREGULATION	450.95	77547	124679	2.482	192472	309454
	451.20	70886	98016	1.980	140355	194072
	451.70	87388	114877	4.118	359864	473062
	452.76	66235	97406	3.907	258779	380566
	453.18	63594	104765	5.122	325726	536605
	454.70	88569	153656	5.069	448955	778881
	455.10	35333	72931	3.168	111934	231045
	455.90	111910	186061	5.438	608567	1011800
	457.16	49553	105806	3.960	196231	418993
	457.40	84680	157951	5.544	469465	875679
	459.26	42087	150649	6.864	288886	1034055
	460.00	53881	170160	6.706	361325	1141095
	TOTAL OF CROSS SECTION AVERAGES				3762559	7385307
WEEKEND REREGULATION	450.95	73329	132554	2.482	182003	328999
	451.20	80721	104477	1.980	159828	206865
	451.70	74259	130592	4.118	305797	537777
	452.76	57225	98729	3.907	223579	385734
	453.18	56743	102630	5.122	290640	525670
	454.70	84761	151504	5.069	429652	767973
	455.10	28679	66713	3.168	90856	211348
	455.90	95187	178543	5.438	517627	970919
	457.16	45235	103901	3.960	179132	411448
	457.40	85219	158154	5.544	472455	876804
	459.26	37197	138745	6.864	255322	952347
	460.00	50608	164423	6.706	339377	1102617
	TOTAL OF CROSS SECTION AVERAGES				3446268	7278502

(continued)

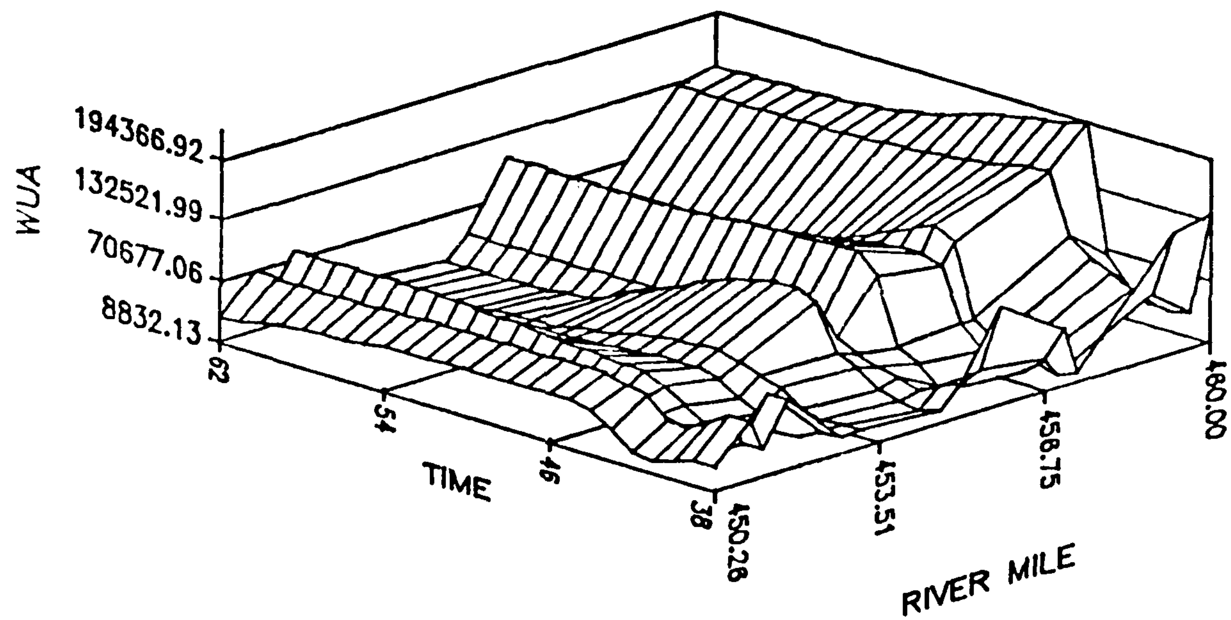
NOTE: Reach multiplier is the length of river represented by each cross section. To obtain average WUA for the reach of river represented by each cross section, multiply the WUA per 1000 ft times the reach multiplier.

Table 3 (concluded)

FLOW CONDITION	RIVER MILE	RAINBOW TR. WUA 1000 FT	BROWN TR. WUA 1000 FT	REACH MULTI-PLIER	RAINBOW TR. WUA C/S TOTAL	BROWN TR. WUA C/S TOTAL
WEEKDAY NONREREGULATION	450.95	53645	68179	2.482	133146	169221
	451.20	30147	36744	1.980	59690	72753
	451.70	77176	67794	4.118	317812	279177
	452.76	38430	33981	3.907	150146	132764
	453.18	34286	39617	5.122	175611	202920
	454.70	57109	48595	5.069	289487	246329
	455.10	41985	44585	3.168	133008	141245
	455.90	122009	94903	5.438	663483	516082
	457.16	61712	66459	3.960	244379	263179
	457.40	58965	50677	5.544	326904	280953
	459.26	62421	124952	6.864	428457	857672
	460.00	108280	133731	6.706	726123	896803
	TOTAL OF CROSS SECTION AVERAGES				3648247	4059097
WEEKEND NONREREGULATION	450.95	56897	67005	2.482	141219	166306
	451.20	33300	34116	1.980	65934	67550
	451.70	84188	71423	4.118	346686	294122
	452.76	33096	28551	3.907	129305	111549
	453.18	30358	32002	5.122	155492	163817
	454.70	37096	32799	5.069	188038	166259
	455.10	41575	42570	3.168	131709	134862
	455.90	127790	97612	5.438	694923	530816
	457.16	62384	65556	3.960	247039	259603
	457.40	35608	34848	5.544	197411	193199
	459.26	63914	125248	6.864	438705	859704
	460.00	120956	134641	6.706	811132	902902
	TOTAL OF CROSS SECTION AVERAGES				3547594	3850790

WOLF CREEK HYDROPOWER UPGRADE STUDY

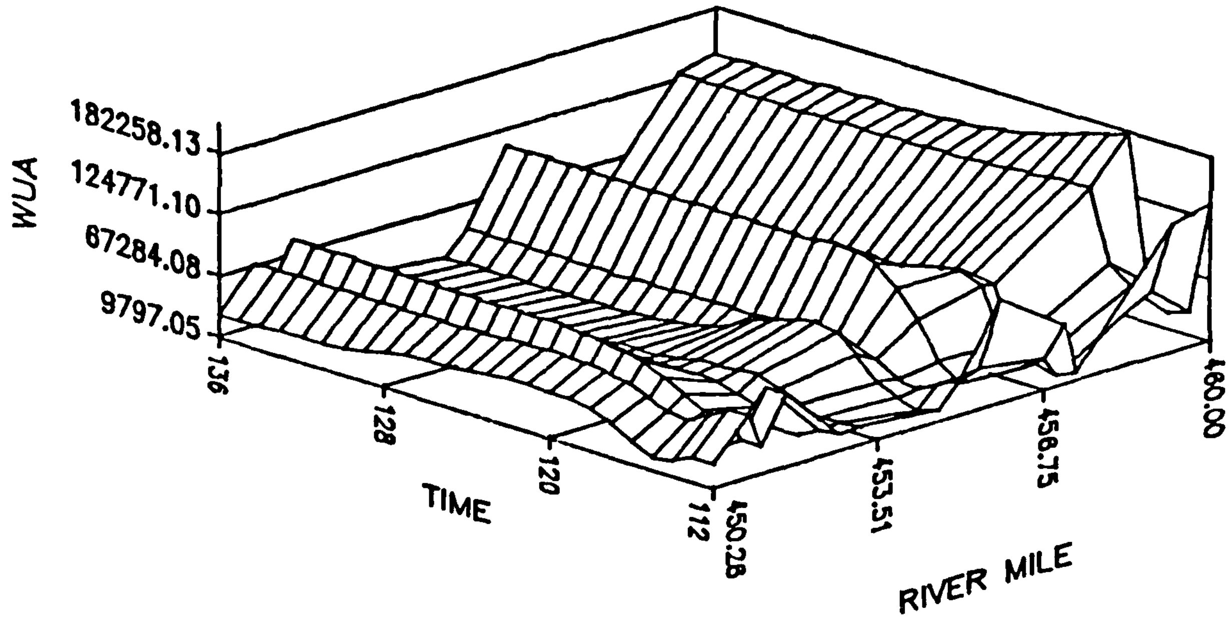
NONREREGULATION CONDITIONS



SPECIES = BROWN TROUT

Figure 1. WUA per 1000 ft of stream versus time versus river mile for adult brown trout under weekday (38 - 62 hours, corresponds to Thursday 2:00 PM to Friday 2:00 PM) nonreregulation conditions for river miles 450.95, 451.20, 451.70, 452.76, 453.18, 454.70, 455.10, 455.90, 457.16, 457.40, 459.26, and 460.00.

WOLF CREEK HYDROPOWER UPGRADE STUDY
NONREREGULATION CONDITIONS



SPECIES = BROWN TROUT

Figure 2. WUA per 1000 ft of stream versus time versus river mile for adult brown trout under weekend (112 - 136 hours, corresponds to Sunday 4:00 PM to Monday 4:00 PM) nonreregulation conditions for river miles 450.95, 451.20, 451.70, 452.76, 453.18, 454.70, 455.10, 455.90, 457.16, 457.40, 459.26, and 460.00.

Habitat conditions in the Cumberland River also vary between weekday and weekend release schedules. Although peaking generation lasts about five hours for both weekday and weekend operations, the high flow conditions associated with weekday operation extend over a longer time period (about 8 hours) than weekend releases because of greater backwater effects associated with the peak weekday flows. Peak weekday flows are approximately 48,000 cfs but peak weekend flows are only 24,000 cfs. Thus, minimum habitat conditions associated with high flows extend for a longer time period on weekday generation compared to weekend generation.

Rainbow Trout

Available habitat for rainbow trout under nonreregulation conditions varies by cross section and by time. Generally, suitable habitat decreases as distance from Wolf Creek Dam increases (Figures 7 and 8).

Changes in discharge over a generation cycle substantially affect the amount of available habitat at each cross section. Habitat is minimal during maximum releases from Wolf Creek Dam. Minimal habitat occurs during the first 8 hours of weekday generation but tends to increase following generation as flows in the Cumberland River decrease. Minimum habitat values range from approximately 3000 to 36,000 sq. ft. of WUA (Table 2, Figures 3 and 4). Average habitat values for rainbow trout for individual cross sections range from 30,000 to 128,000 sq. ft. of WUA with most values ranging from 30,000 to 64,000 sq. ft. (Table 3, Figures 5 and 6).

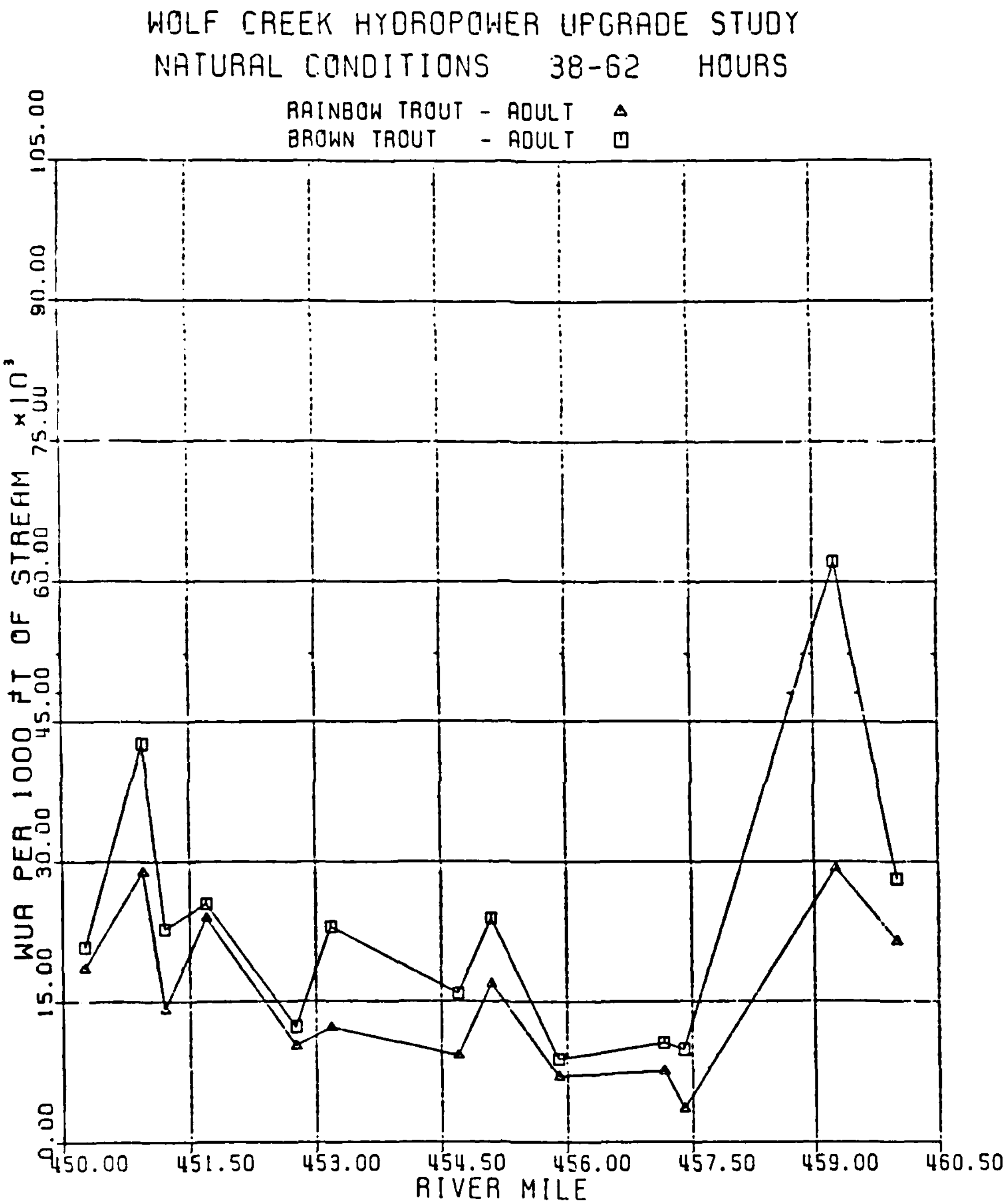


Figure 3. Minimum WUA for adult rainbow trout and brown trout under weekday (38 hours - 62 hours, corresponds to Thursday 2:00 PM to Friday 2:00 PM) nonreregulation conditions in the Cumberland River from river mile 450.26 to 460.00.

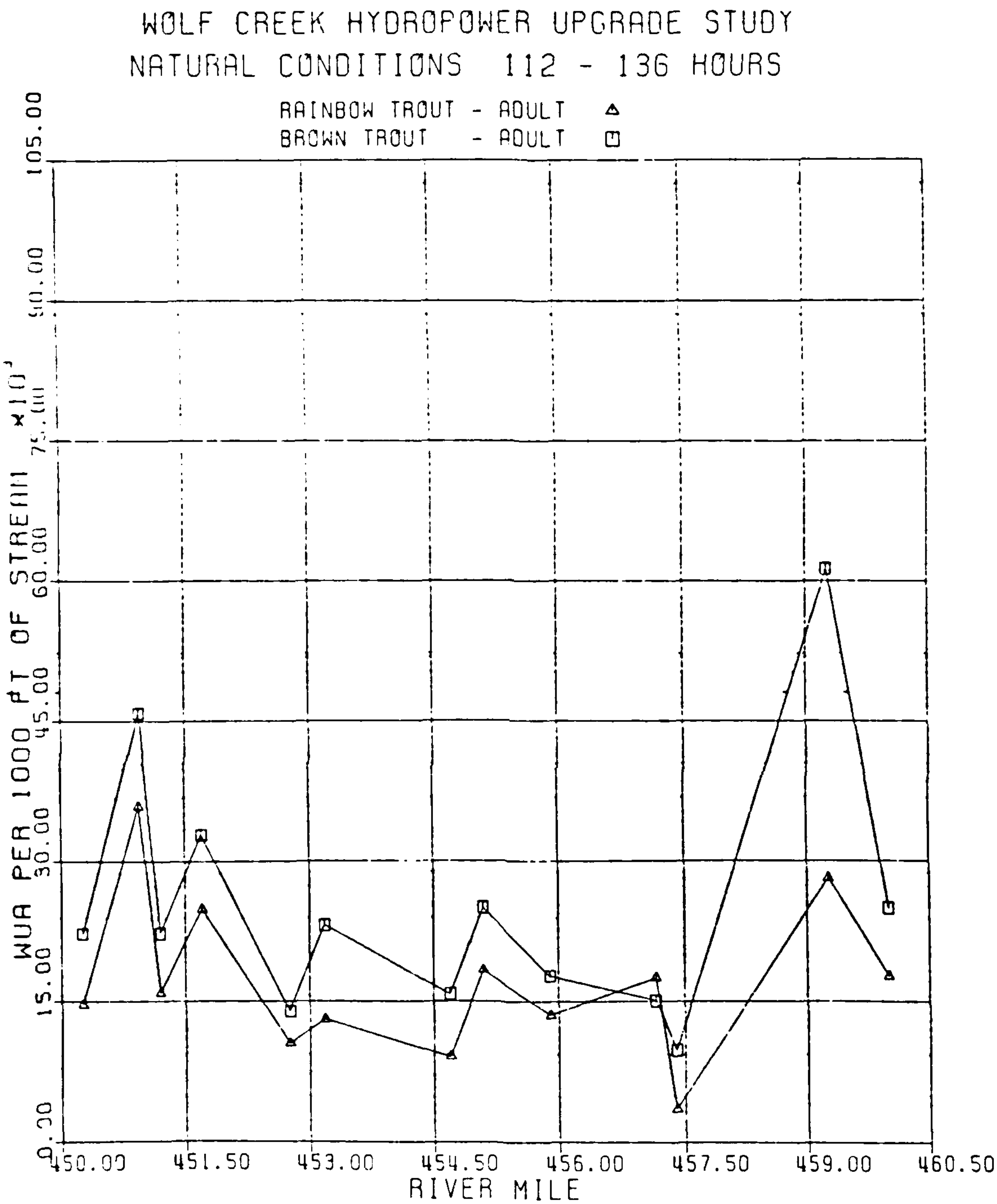


Figure 4. Minimum WUA for adult rainbow trout and brown trout under weekend (112 hours - 136 hours, corresponds to Sunday 4:00 PM to Monday 4:00 PM) nonreregulation conditions in the Cumberland River from river miles 450.26 to 460.00.

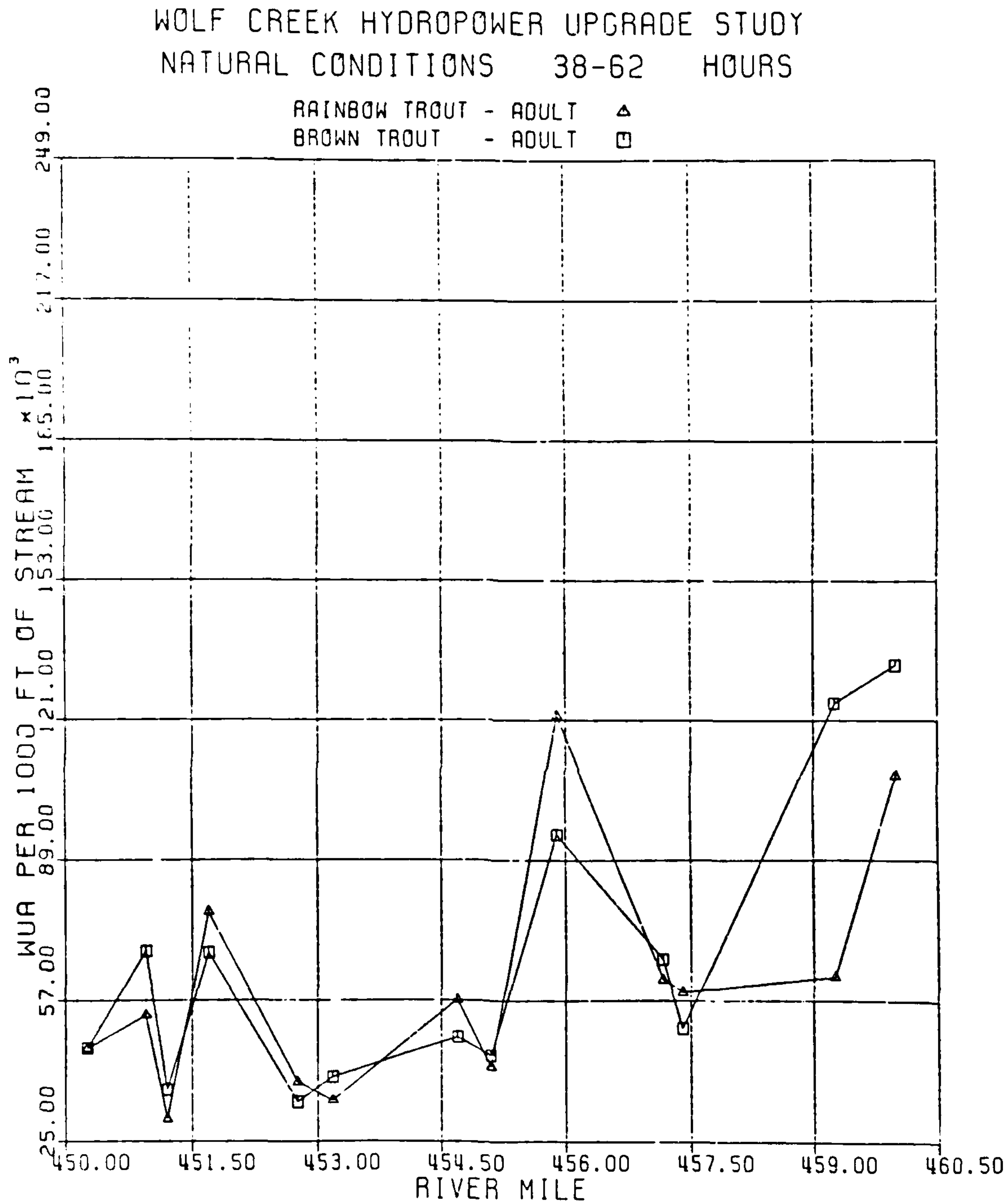


Figure 5. Average WUA for adult rainbow trout and brown trout under weekday (38 hours - 62 hours) nonreregulation conditions in the Cumberland River from river miles 450.26 to 460.00.

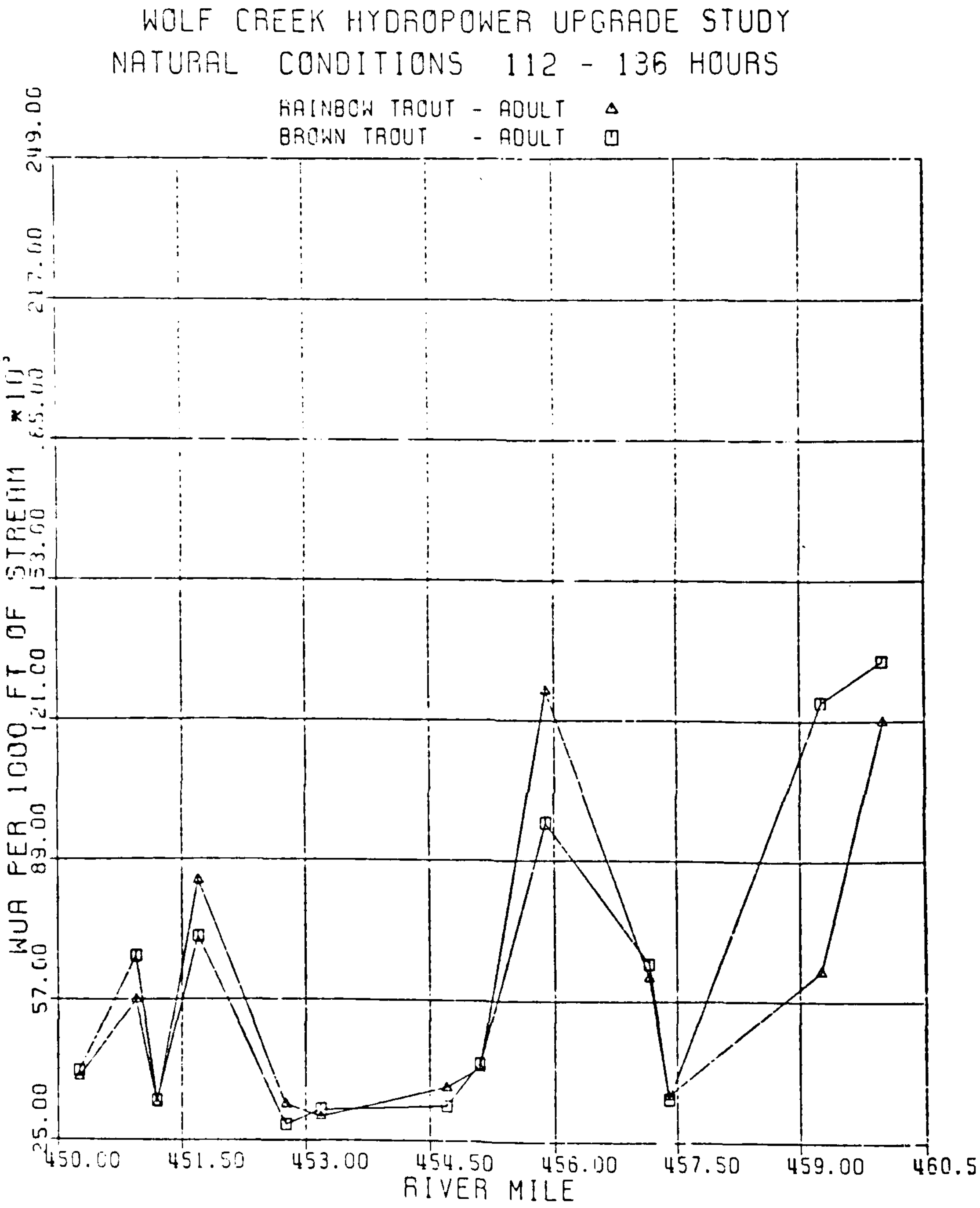


Figure 6. Average WUA for adult rainbow trout and brown trout under weekend (112 hours - 136 hours) nonreregulation conditions in the Cumberland River from river miles 450.26 to 460.00.

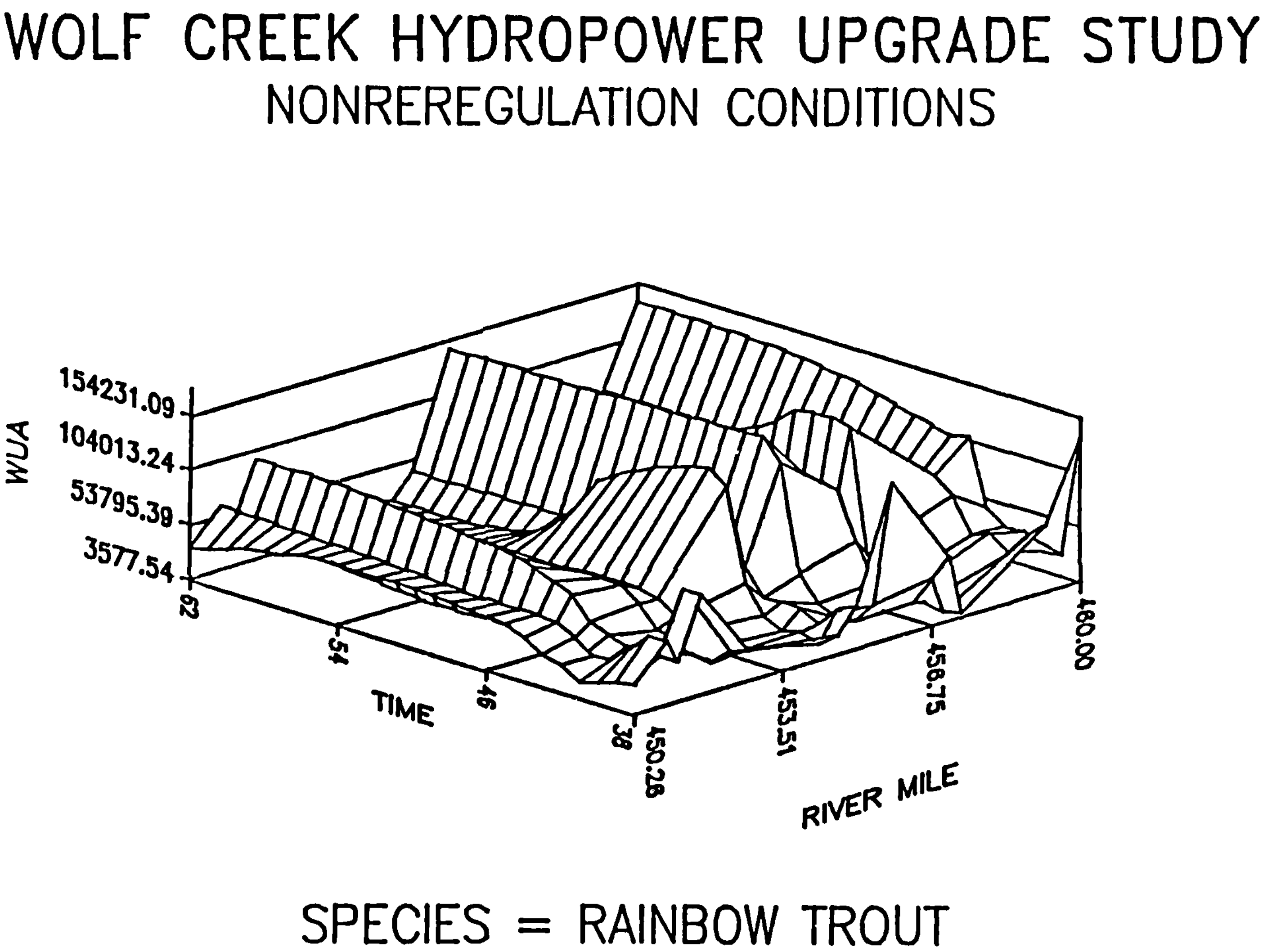


Figure 7. WUA per 1000 ft of stream versus time versus river mile for adult rainbow trout under weekday, nonreregulation conditions (See Figure 1 for times and river miles).

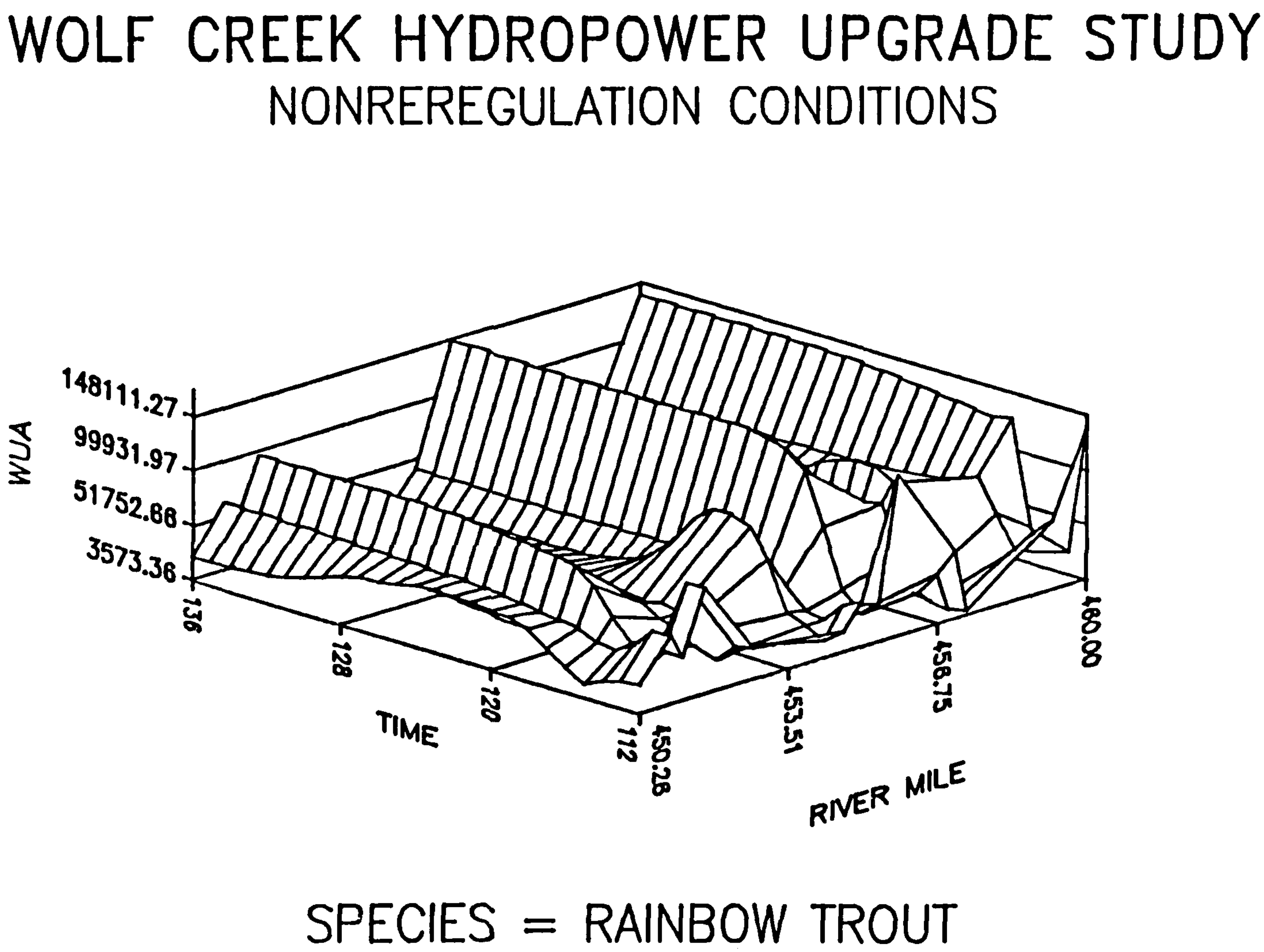


Figure 8. WUA per 1000 ft of stream versus time versus river mile for adult rainbow trout under weekend, nonreregulation conditions (See Figure 2 for times and river miles).

Available habitat in the Cumberland River also varies between weekday and weekend generation. As with brown trout, the minimum habitat for rainbow trout during weekday generation is extended compared to weekend generation because of the high releases from the dam during weekday scheduling. The peak releases from Wolf Creek Dam during the weekend are 24,000 cfs while the peak weekday flows are 48,000 cfs.

Juvenile Brown Trout

Juvenile brown trout revealed no noticeable trends under nonreregulation conditions with distance from Wolf Creek Dam (Figures 9 and 10). Generally, habitat was minimal at all cross sections during generation.

Hydropower Modification With Reregulation

General Results

The general results for adult brown trout and rainbow trout under reregulation conditions follow the same trend though brown trout habitat values are greater than rainbow trout at most cross sections. In most cases, habitat for each species was at a minimum during high flows from Wolf Creek Dam and at a maximum during low and intermediate flow periods. As with nonreregulation conditions, juvenile brown trout exhibited the least amount of habitat in this river reach.

Brown Trout

Habitat for adult brown trout under reregulation conditions is consistently greater than under nonreregulation conditions (Tables 2 and 3). In general,

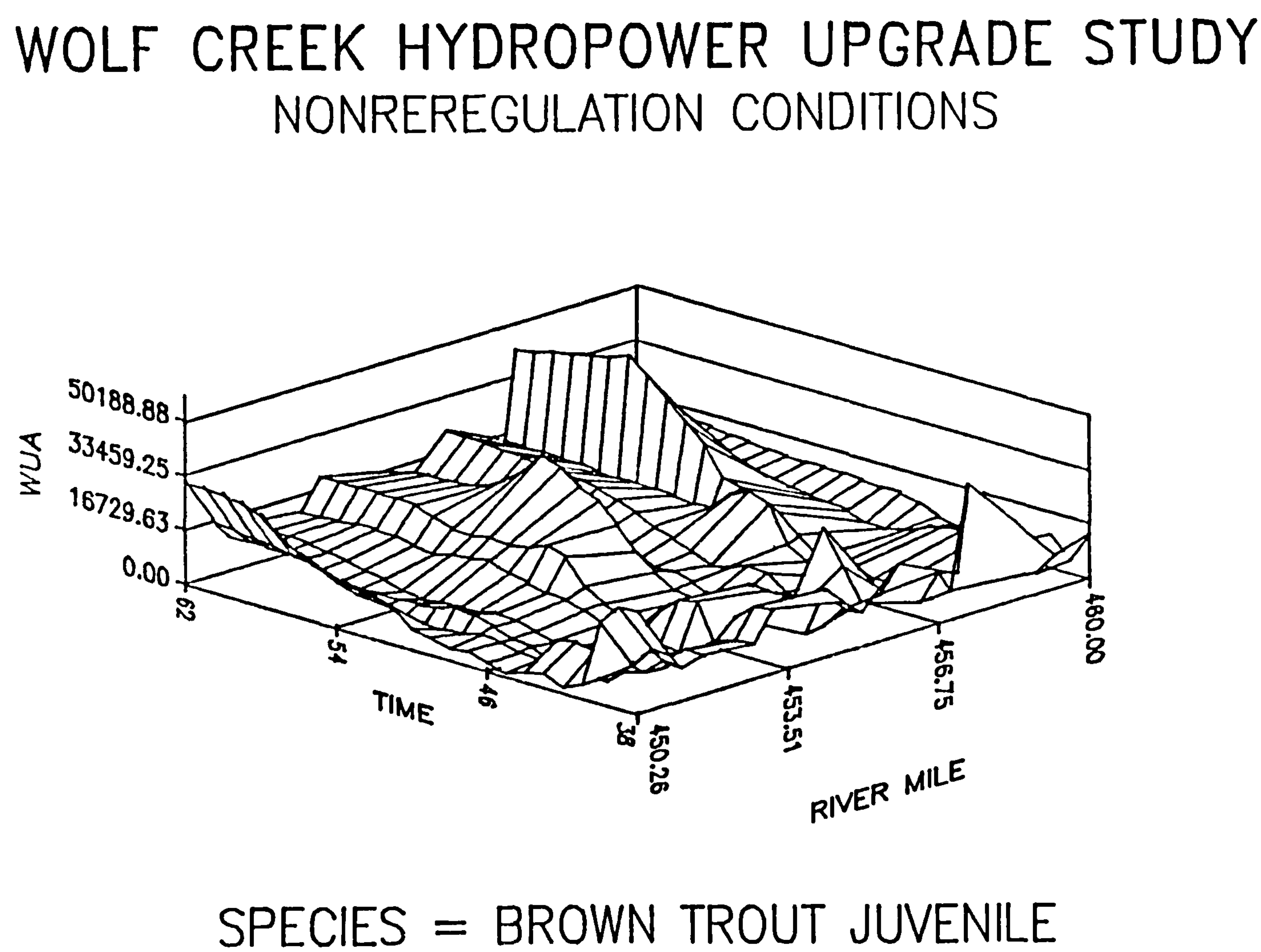


Figure 9. WUA per 1000 ft of stream versus time versus river mile for juvenile brown trout under weekday, nonreregulation conditions (See Figure 1 for times and river miles).

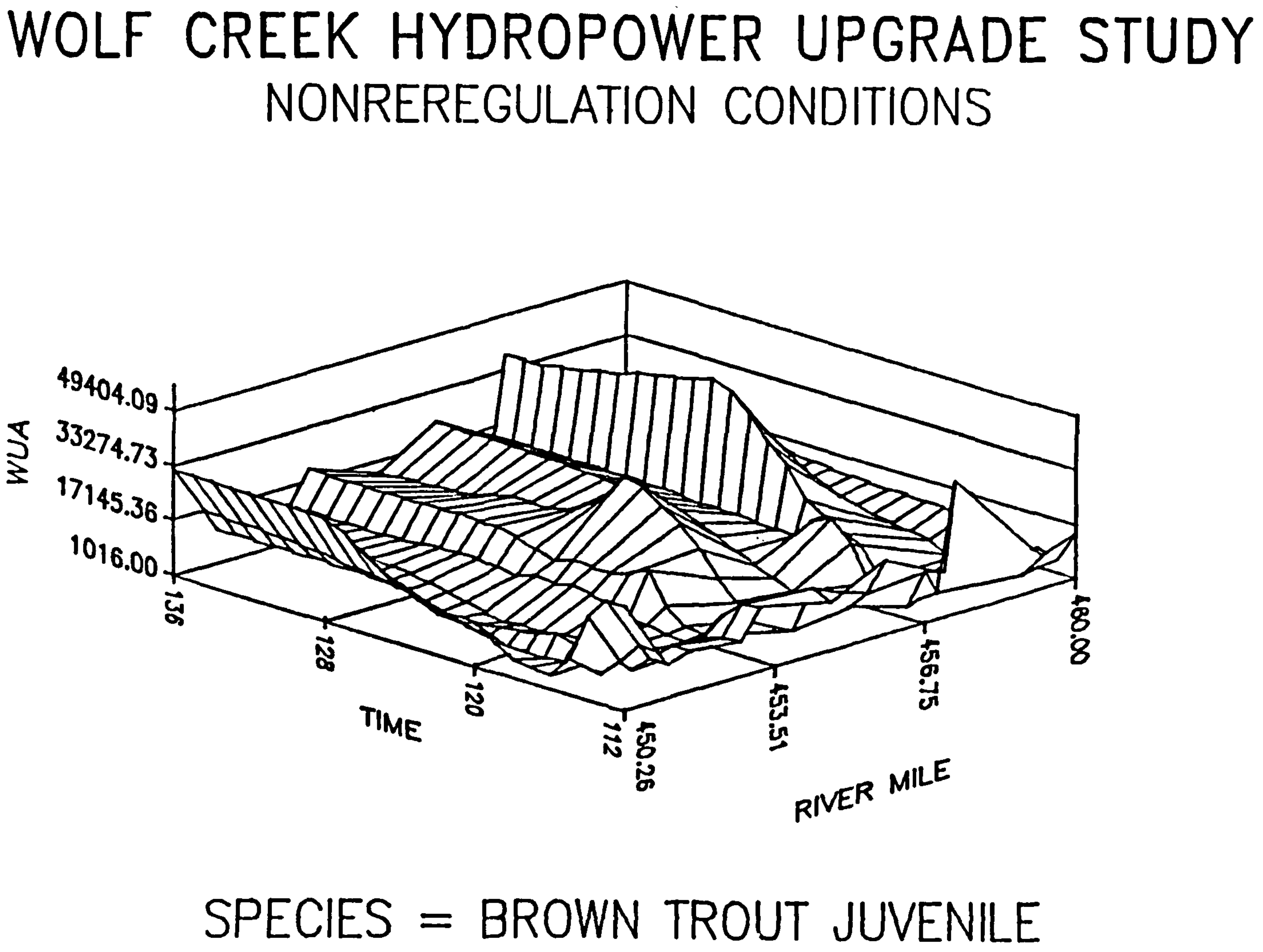


Figure 10. WUA per 1000 ft of stream versus time versus river mile for juvenile brown trout under weekend, nonreregulation conditions (See Figure 2 for times and river miles).

habitat appears to decrease with increasing distance from Wolf Creek Dam (Figures 11 and 12).

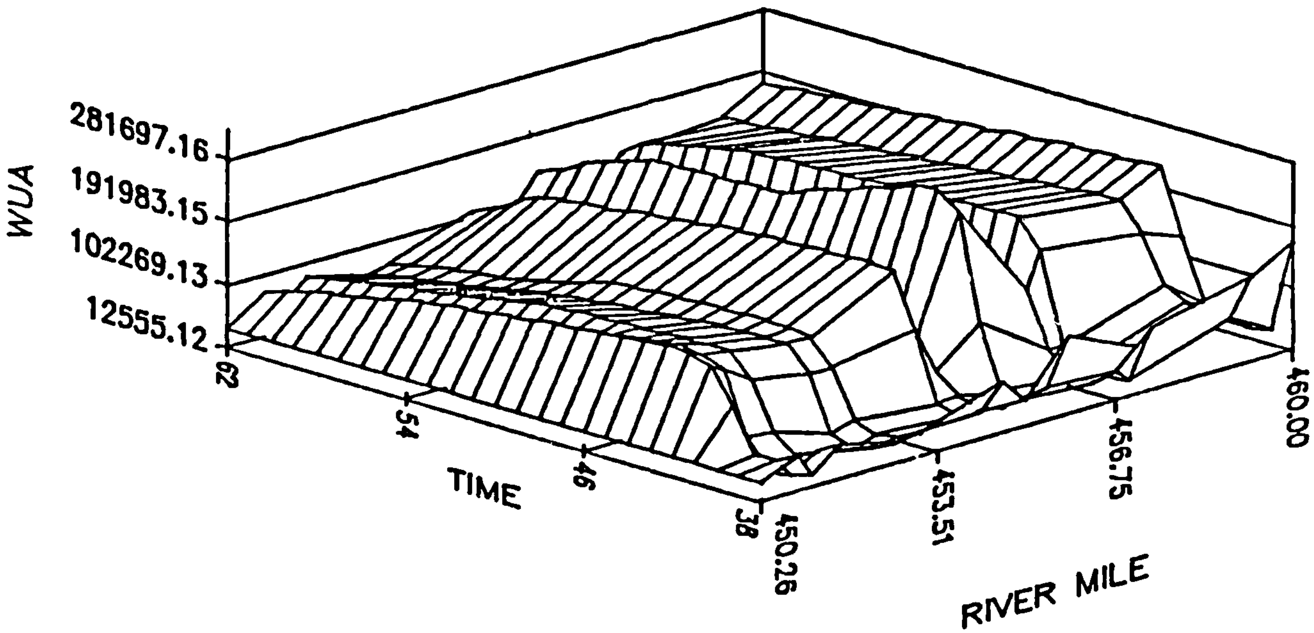
Average habitat values for brown trout range from 66,000 to 186,000 sq. ft. while most values vary from 90,000 to 160,000 sq. ft. of WUA (Table 3, Figures 13 and 14). Habitat is minimal during the first four hours of weekday generation but tends to increase and remain steady for the remainder of the time period. Habitat varied less between weekend and weekday generation schedules under reregulation than under nonreregulation. During weekend generation habitat approached 205,000 sq. ft. of WUA and during weekday operation habitat approached 190,000 sq. ft. of WUA (Figures 11 and 12). Maximum releases during the week are 48,000 cfs compared to 24,000 cfs during weekend hours.

Rainbow Trout

Habitat for rainbow trout, measured as average habitat for each cross section, is also greater under reregulation than under nonreregulation (Table 3). However, habitat as measured by minimum habitat available for each cross section, shows little difference between reregulation and nonreregulation. Available habitat values for rainbow trout under reregulation conditions vary with distance and by time. Generally, habitat values appear to fluctuate during the first 5 hours of weekday generation and the first 4 hours of weekend generation after which time habitat becomes steady at most cross sections (Figures 15 and 16).

Habitat is minimal for some cross sections (Table 2, Figures 17 and 18) during maximum releases from Wolf Creek Dam. Average habitat values for rainbow trout vary from 28,000 to 112,000 sq. ft. of WUA while most values range from 40,000 to 78,000 sq. ft. of WUA (Table 3, Figures 13 and 14).

WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS



SPECIES = BROWN TROUT

Figure 11. WUA per 1000 ft of stream versus time versus river mile for adult brown trout under weekday, reregulation conditions (See Figure 1 for times and river miles).

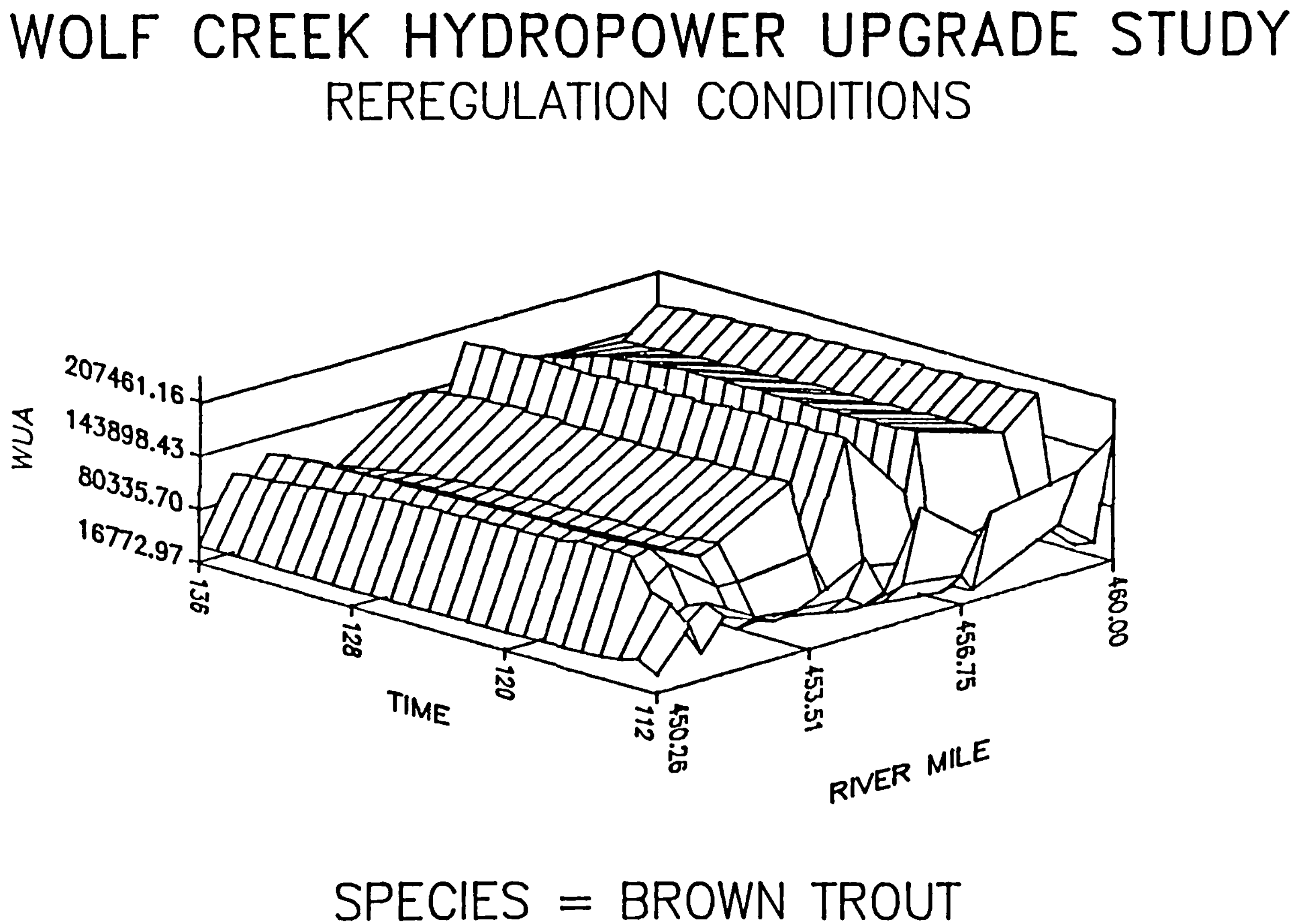


Figure 12. WUA per 1000 ft of stream versus time versus river mile for adult brown trout under weekend, reregulation conditions (See Figure 2 for times and river miles)

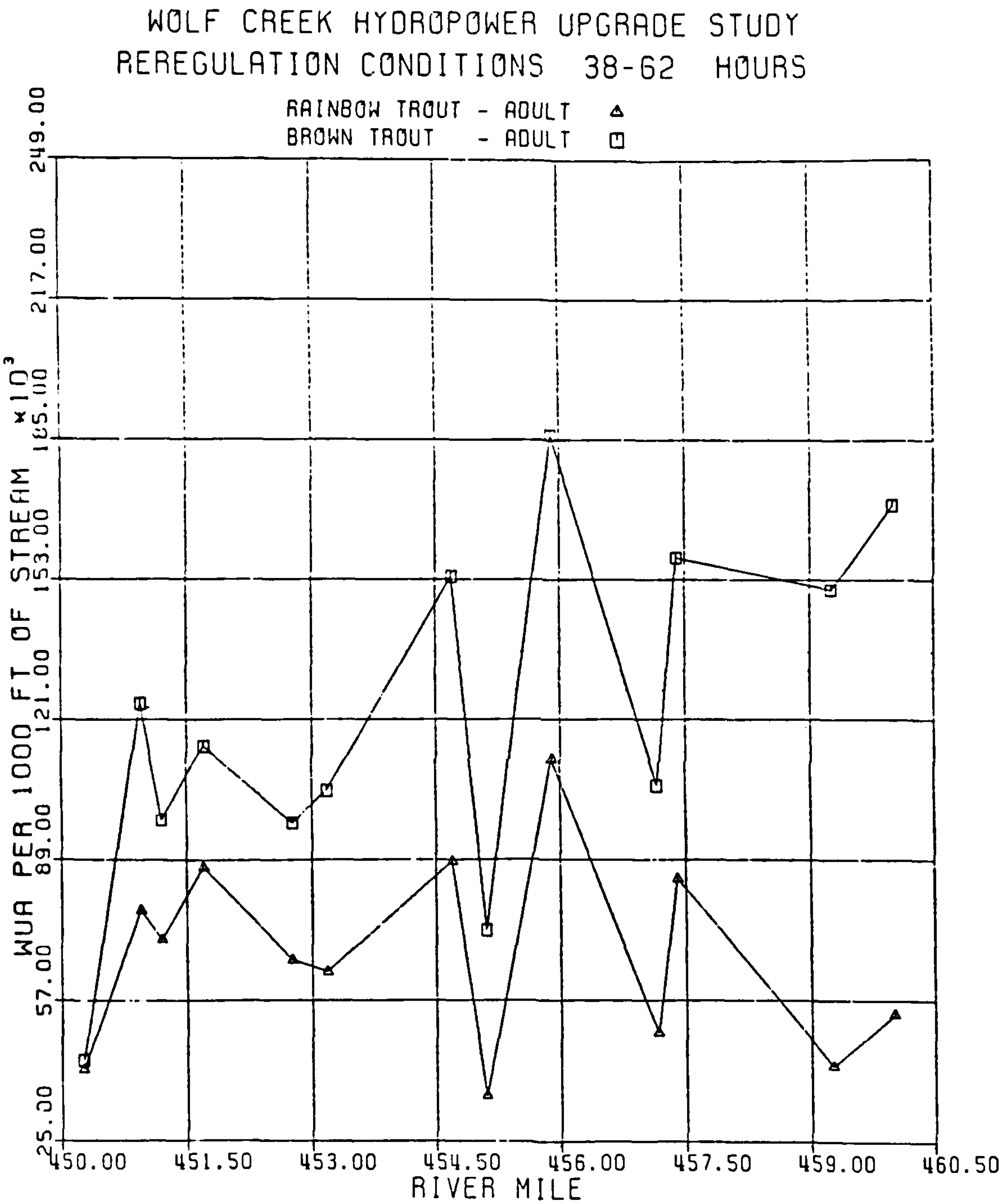


Figure 13. Average WUA for adult rainbow trout and brown trout under weekday (38 hours - 62 hours) reregulation conditions in the Cumberland River from river miles 450.26 to 460.00.

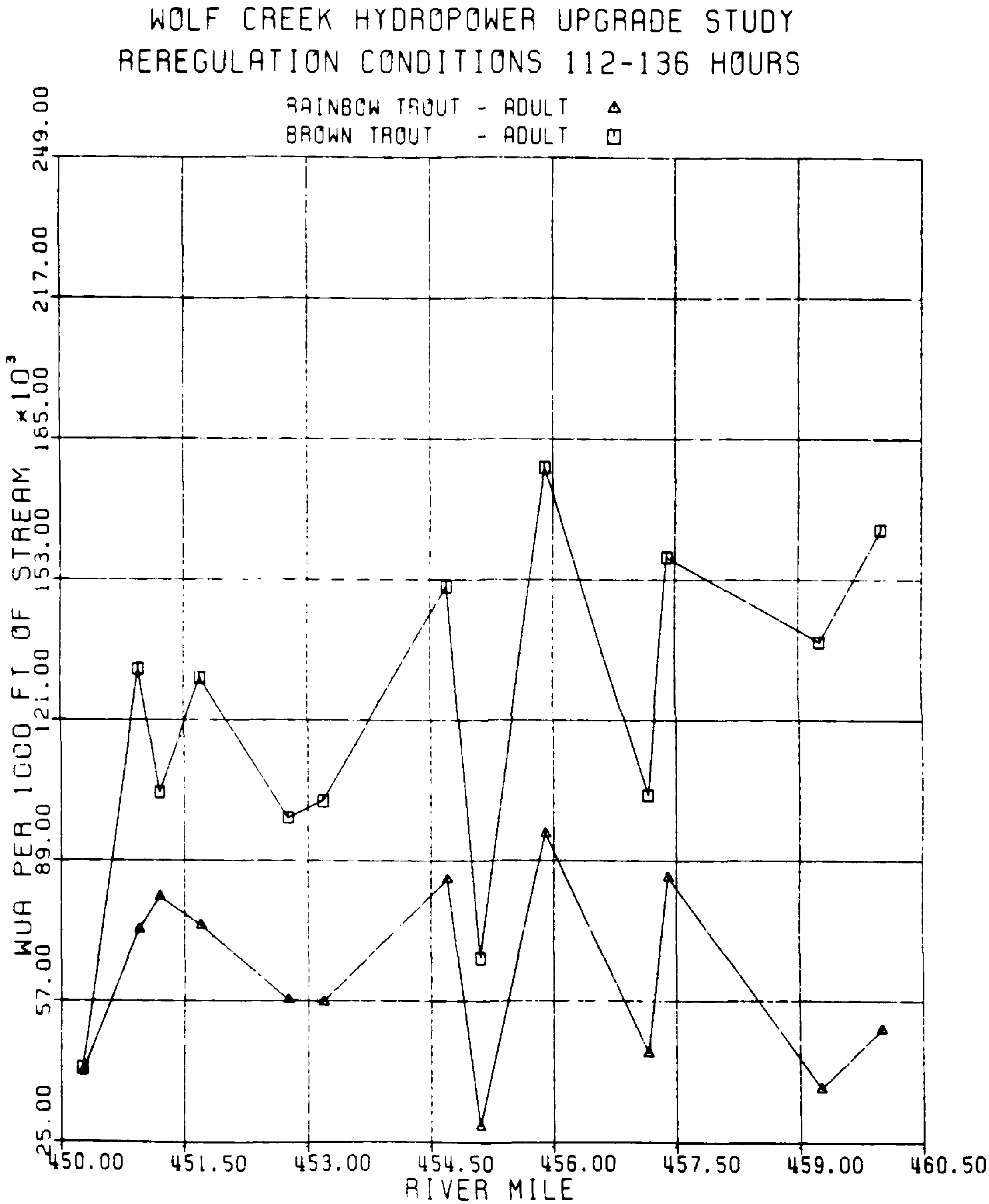


Figure 14. Average WUA for adult rainbow trout and brown trout under weekend (112 hours - 136 hours) reregulation conditions in the Cumberland River from river miles 450.26 to 460.00.

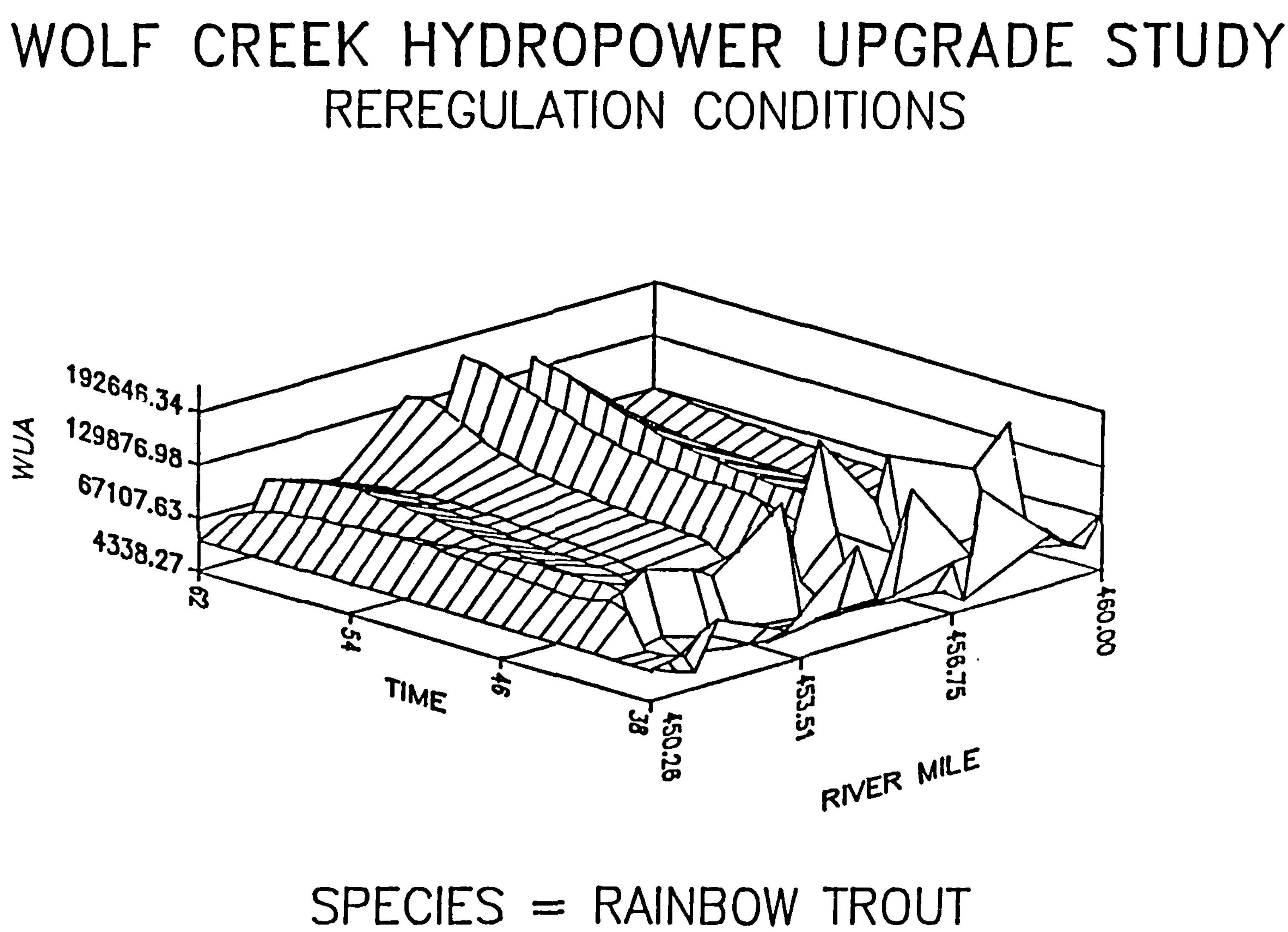
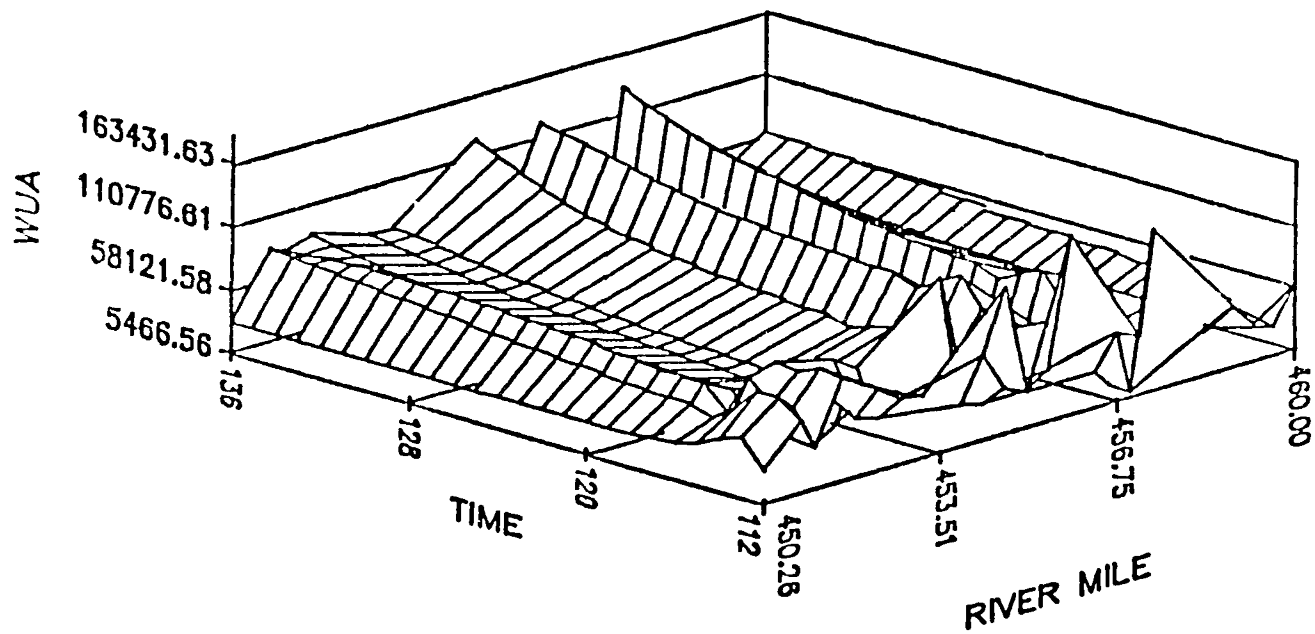


Figure 15. WUA 1000 ft of stream versus time versus river mile for adult rainbow trout under weekday, reregulation conditions (See Figure 1 for times and river miles).

WOLF CREEK HYDROPOWER UPGRADE STUDY

REREGULATION CONDITIONS



SPECIES = RAINBOW TROUT

Figure 16. WUA 1000 ft of stream versus time versus river mile for adult rainbow trout under weekend, reregulation conditions (See Figure 2 for times and river miles).

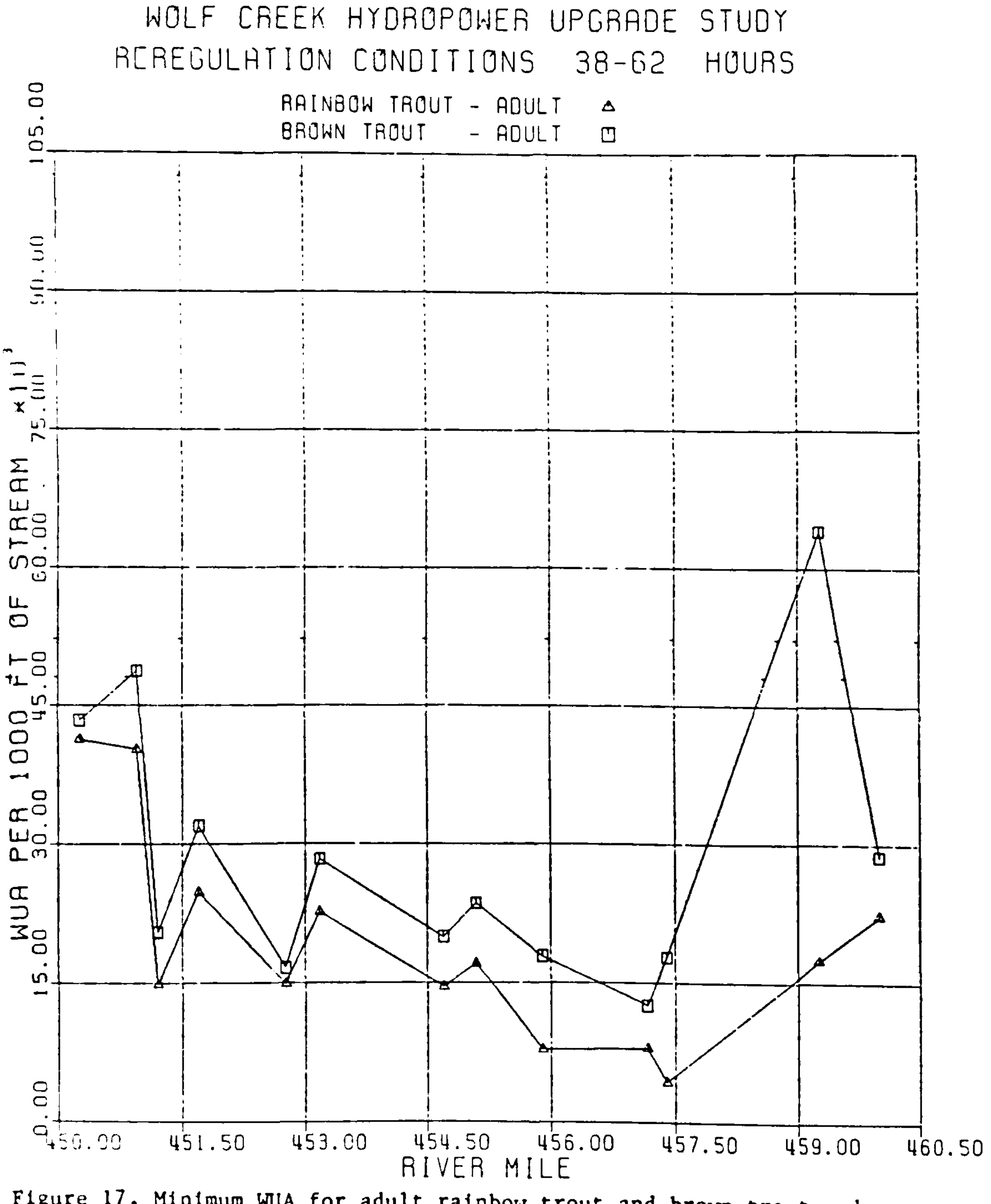


Figure 17. Minimum WUA for adult rainbow trout and brown trout under weekday (38 hours - 62 hours) reregulation conditions in the Cumberland River from river miles 450.26 to 460.00.

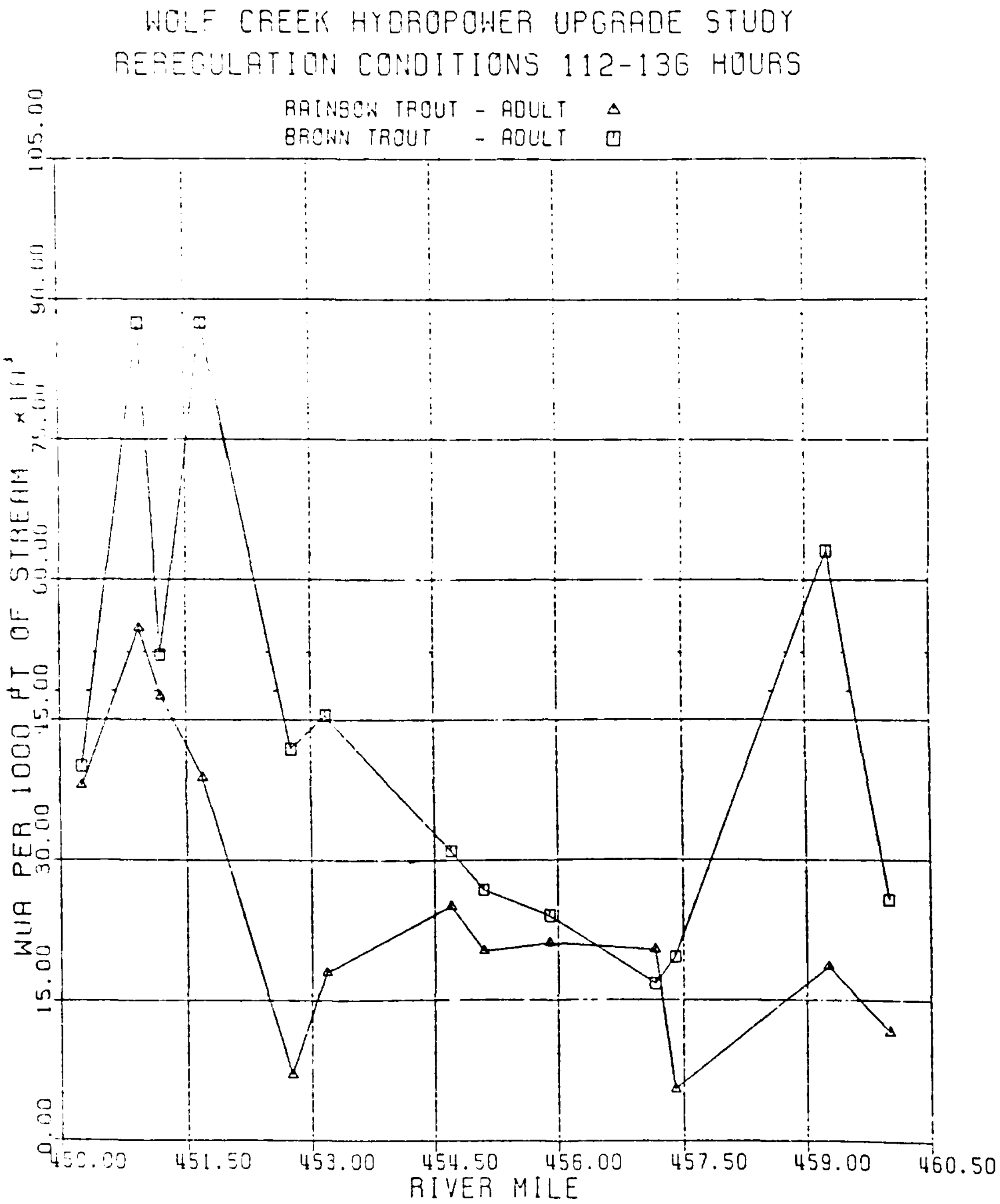


Figure 18. Minimum WUA for adult rainbow trout and brown trout under weekend (112 hors - 136 hours) reregulation conditions in the Cumberland River from river miles 450.26 to 460.00.

Habitat conditions in the Cumberland River below Wolf Creek Dam vary between weekday and weekend generation schedules. Minimal habitat occurs for a longer period of time during the weekday cycle than during the weekend cycle because of the increased peak flow of 48,000 cfs and peak flow conditions of 5 hours (Figures 15 and 16). Minimal habitat values range from 4300 to 55,000 sq. ft. of WUA (Table 2). During weekend operation, peak flows are only 24,000 cfs and last for about 5 hours.

Juvenile Brown Trout

Similar to the results obtained under nonreregulation conditions, juvenile brown trout under reregulation conditions exhibited no trends with distance from Wolf Creek Dam. Habitat values appeared to be sporadic at most cross sections during both weekday and weekend schedules (Figures 19 and 20).

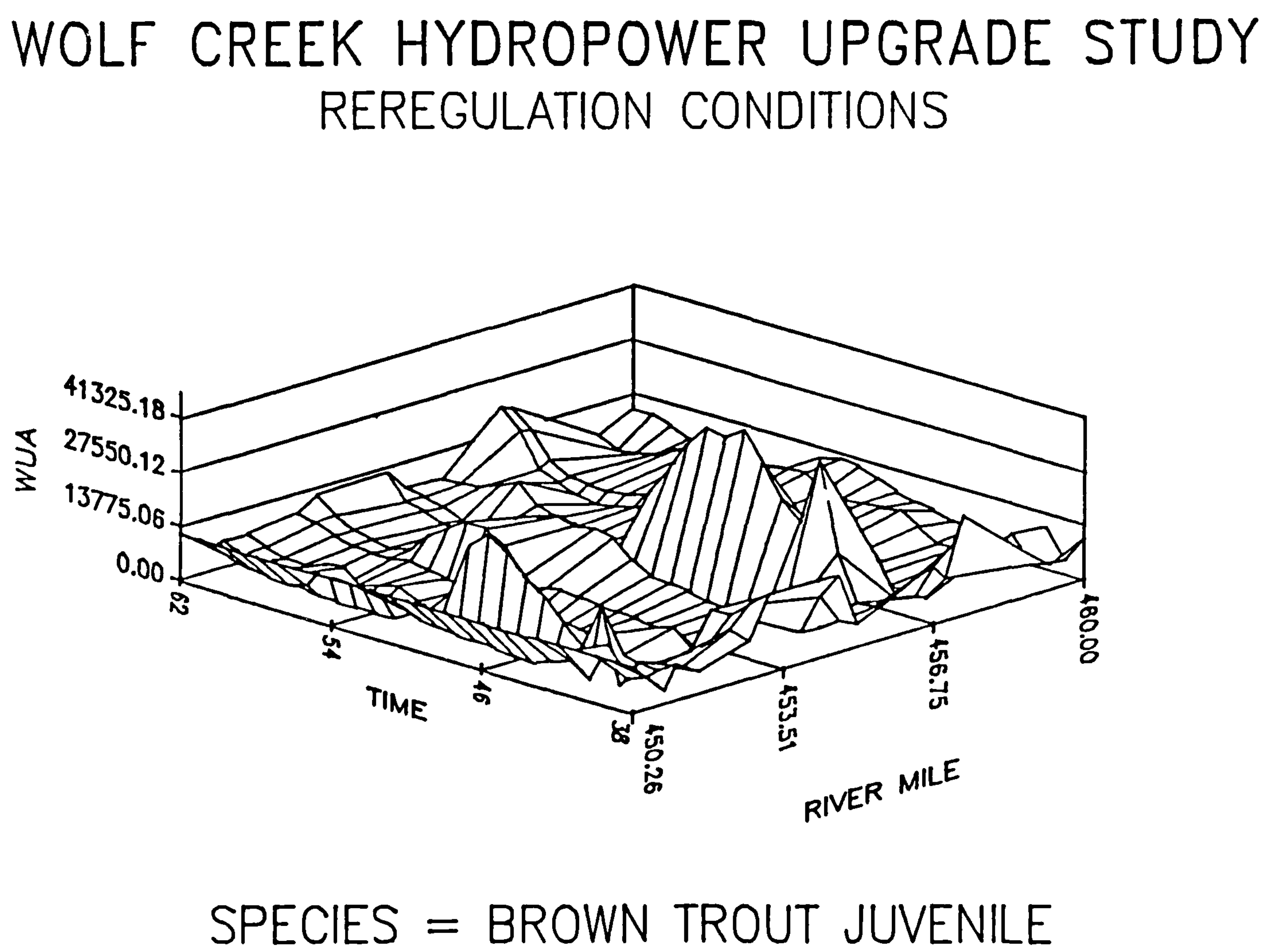


Figure 19. WUA per 1000 ft of stream versus time versus river mile for juvenile brown trout under weekday, reregulation conditions (See Figure 1 for times and river miles).

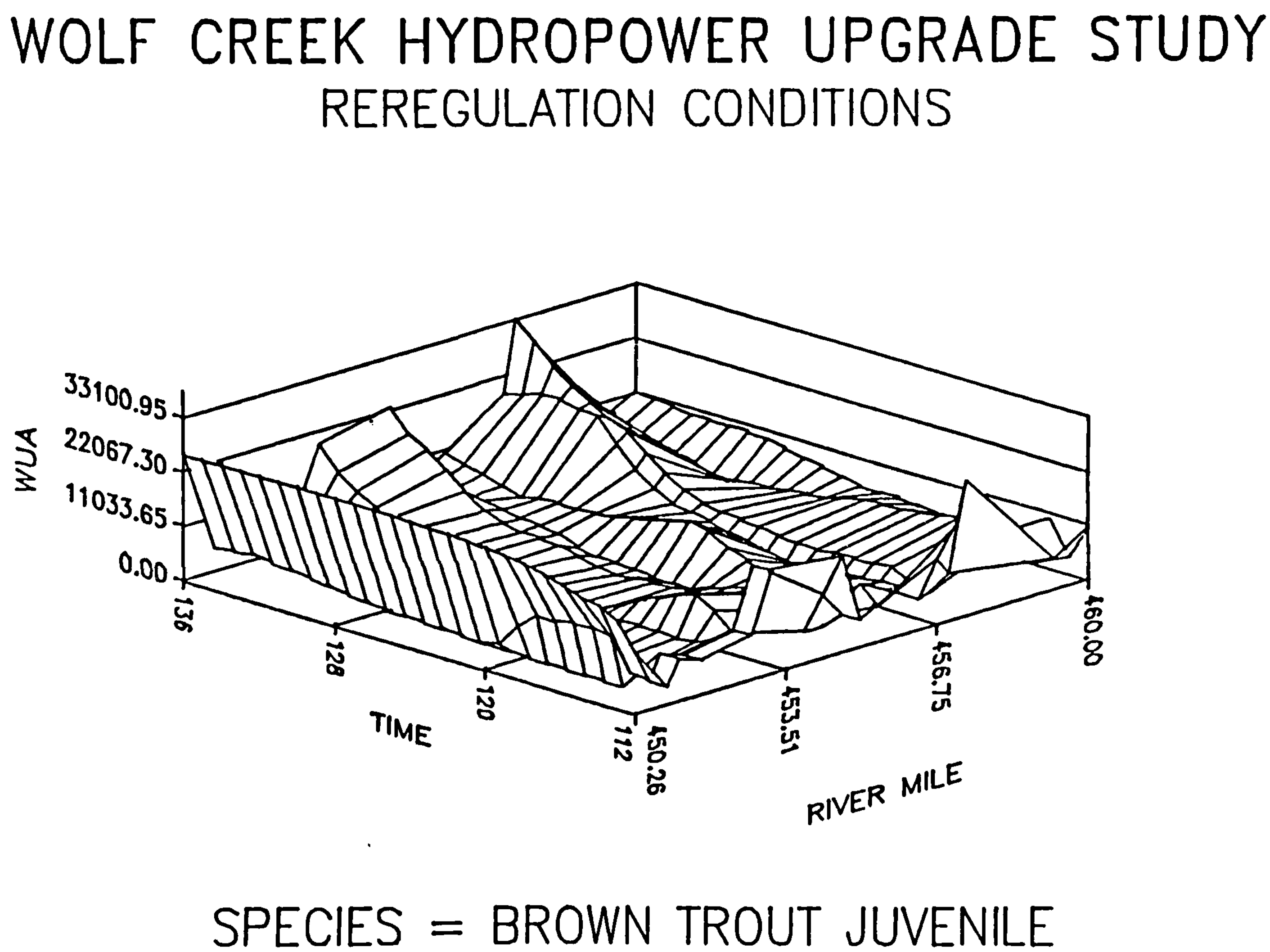


Figure 20. WUA 1000 ft of steam versus time versus river mile for juvenile brown trout under weekend, reregulation conditions (See Figure 2 for times and river miles).

PART IV: DISCUSSION

Life Stage Differences

The general results for the three life stages evaluated in this report are primarily determined by the range of depths and velocities that each can tolerate. Adult brown trout have the broadest criteria for both depth and velocity (see Appendix A for suitability curves) and thus generally have the most habitat available under flow conditions associated with both reregulation and nonreregulation (Figures 1, 2, 11, and 12). Adult rainbow trout have slightly narrower velocity requirements than brown trout and thus have slightly less habitat available under most flow conditions (Figures 7, 8, 15 and 16). Juvenile brown trout have the narrowest criteria for both depth and velocity and thus have substantially less habitat under both reregulation and nonreregulation than either adult brown trout or adult rainbow trout. In fact, juvenile brown trout habitat do not exhibit any discernible patterns by time or distance under either reregulation or nonreregulation (Figures 9, 10, 19, and 20).

Fish habitat predictions under dynamic flow conditions are difficult to summarize because of the complex flow conditions in the river and because other case history studies are unavailable for comparison. Thus, the manner that habitat values should be summarized to best relate changes in flow conditions to impacts on fish is not completely known. Adult brown trout and adult rainbow trout habitat can probably be best represented as habitat summaries over time for each cross section. Adults of these two species are strong swimmers and have relatively broad habitat requirements and thus, can probably relocate to avoid

local habitat minima during a generation cycle. Juvenile brown trout, on the other hand, have narrow habitat requirements and do not have the swimming ability of adults; therefore, the effects of different flow conditions are best represented as the minimum habitat available for each cross section over a generation cycle. In this report, however, minimum habitat values were not calculated for juvenile brown trout since the results for this life stage exhibited no discernible trends (Figures 9, 10, 19, and 20).

Temporal and Spatial Distribution of Habitat

Peaking operation at Wolf Creek Dam under hydropower upgrade can be broadly categorized as generation and nongeneration. During generation, flows increase suddenly, remain high for up to several hours, and then decline to a base flow. The generation flow consistently has the greatest negative impact on trout habitat downstream of Wolf Creek Dam because the high velocities associated with peak discharges exceed the tolerance limits for the lifestages/species studied. The duration of the peak release determines the length of the habitat minimum that occurs at each cross section.

Habitat for adult brown trout and adult rainbow trout varies by distance under hydropower upgrade conditions both under reregulation and nonreregulation. Longitudinal differences in habitat result from two opposing factors. Downstream channel morphology and substrate has less fractured bedrock, boulders, rocks and cobble which translate into decreasing cover with distance downstream of the dam. However, flow conditions also change with increasing distance from Wolf Creek Dam. Maximum discharge decreases downstream as the power wave attenuates with a concomitant increase in the low flow. Thus, the high velocities that limit trout during generation are reduced as the peak release flows downstream.

Effects of Reregulation

The predicted responses of adult brown trout and adult rainbow trout are sufficiently similar that both can be discussed together. More habitat is consistently available for both lifestages under reregulation than under nonreregulation for the projected discharges from Wolf Creek Dam. Several factors associated with reregulation are responsible for an increase in trout habitat.

First, a reregulation dam that maintains a minimum pool produces a backwater effect upstream of the site of the reregulation dam. The extent of the backwater effect is determined by the size of the pool upstream of the reregulation dam. The backwater effect generally results in a decrease in the high water velocities associated with peaking operation through this reach and particularly near the reregulation dam. In fact, discharge just upstream of the reregulation dam varies only between 6,000 to 8,000 cfs over the projected weekday generation cycle.

Second, reregulation decreases the rate of change of both discharge and water surface elevation during a generation cycle upstream of the reregulation dam. Extreme fluctuations in water surface elevation are known to have a detrimental effect on aquatic organisms both through stranding and desiccation and also through changes in the channel, such as bank sloughing.

The beneficial effects of reregulation, as described above, are inexorably related to the design and operation of the reregulation dam. If the hydraulic conditions provided by ORN as being representative of reregulation are altered, then these beneficial effects could be lost. For example, if a permanent pool

behind the reregulation dam is not maintained then the beneficial effects of reregulation will be replaced by the same extreme flow fluctuations seen without reregulation plus dewatering and attendant stranding and desiccation. The direct relationship between hydraulic conditions upstream of the reregulation dam and trout habitat in the pool of the reregulation dam suggests that trout habitat be carefully considered in designing and operating the proposed reregulation dam.

Other Considerations

Comparison between hydropower modification and peaking operation with and without reregulaton involves factors other than changes in habitat caused by releases from Wolf Creek Dam. Other factors that may differ between reregulation and nonreregulation include water quality, effects on benthos, and changes in physical habitat. Most of these factors cannot be quantified without further, more detailed study.

Water quality conditions in the study reach may differ between reregulation and nonreregulation. However, water quality differences are probably not substantial since the travel time of water in the study reach under both alternatives is similar. Water quality differences, particularly temperature, are discussed in detail by Martin (1985).

The benthic community may also react differently to reregulated versus nonreregulated conditions. Although the response of the benthic community cannot be quantified, several qualitative statements can be made. First, benthic biomass abundance (particularly those groups that provide the best food base for fish, such as mayflies, stoneflies, and caddisflies) is reduced in the fluctuation zone in the tailwaters of peaking hydropower projects. Thus,

hydropower modification without reregulation would probably have the more deleterious effects on the benthos, since more of the river channel would be exposed. That is, water surface elevations without reregulation are lower than water surface elevations with reregulation.

Study Limitations

This study, like any study that purports to predict the effects of future actions, is limited both by inherent short-comings in the quantitative methods that were used and by assumptions that were made in the course of the study. A partial list of study limitations is listed below.

(a) The predictions of trout habitat made in this report are probably relative and not absolute since habitat projections were made at .6 depth and most trout are found deeper in the water column.

(b) The detrimental effects of hydropower modification without reregulation are probably over-estimated near the dam as are the effects of the releases associated with peaking operation. The large rocks, fractured bedrock and boulders that occur in the channel provide refuges for trout from the high velocities associated with generation time periods.

(c) Habitat is assumed to change instantly with flow in this study. In fact, the ability to predict physical habitat under dynamic flow conditions probably exceeds an understanding of how fish actually react during a generation cycle at various locations in a tailwater. Thus, for both this reason and the reason presented in (a), the results presented in this report are probably relative in nature. That is, the habitat values presented in this report for a given operation are not absolute; however, they should be adequate for making relative comparisons between operation plans.

(d) The suitability curves used in this curve were obtained from a previous study and were assumed to apply to the Cumberland River trout fishery. This assumption was not tested.

(e) The cross sections used as a basis for predicting trout habitat under different alternatives were originally selected for purposes of developing elevation capacity information and to provide data for hydraulic simulation. This study assumes that no critical areas were omitted and that these cross sections are adequate for representing trout habitat in the Cumberland River.

PART V: CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations of this study are as follows.

(a) More adult brown trout and adult rainbow trout habitat (includes minimum habitat, average habitat, and maximum habitat) is available under hydropower modification with reregulation than under modification without reregulation.

(b) Changes in juvenile brown trout habitat were inconsistent and clear conclusions could not be formed for this life stage.

(c) The fisheries benefits of reregulation are directly related to the backwater effects of the reregulation dam which, in turn, are directly related to the specific operation of the reregulation dam.

(d) Trout habitat within the study reach is highly dependent on day-to-day operation of Wolf Creek Dam as well as potential operation of a reregulation dam. Therefore, the conclusions of this study are based upon the two operation scenarios provided by the ORN. Other scenarios may generate different results depending upon the details of operation.

(e) Consideration should be given to developing operation guidelines for reregulation during CPE (if a reregulation dam is constructed) to protect trout habitat within the study reach since trout habitat is so highly dependent upon operations.

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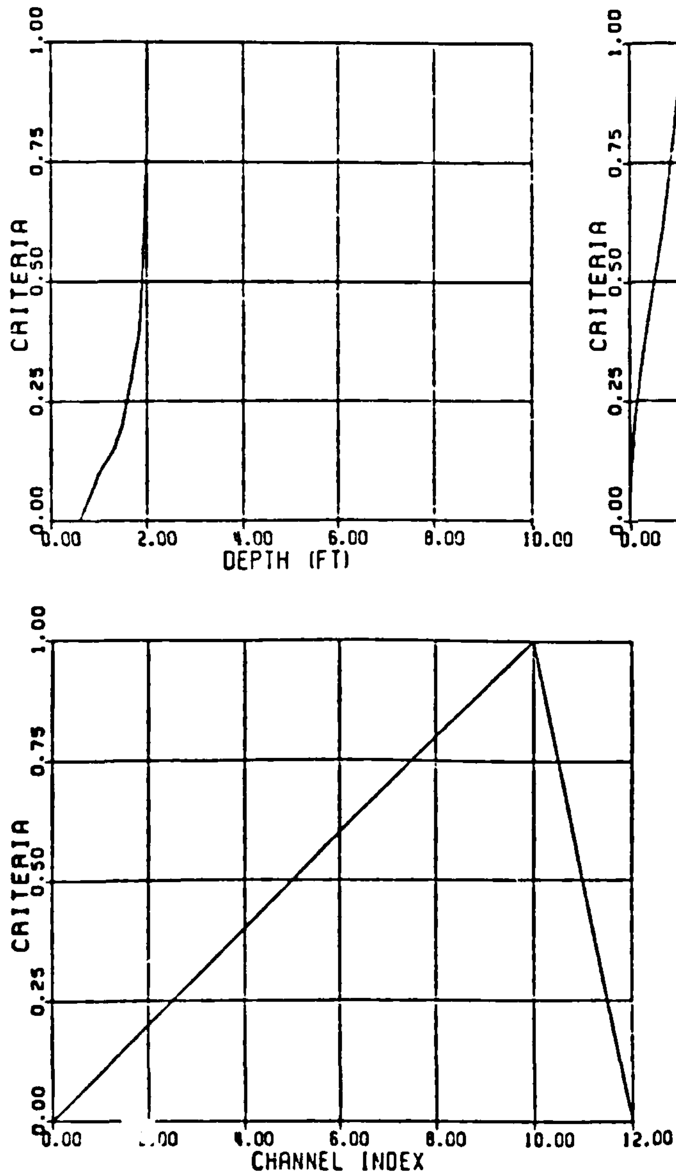
Milhous, R. T., D. L. Wegner, and Terry Waddle. 1984. Users Guide to the Physical Habitat Simulation System (PHABSIM). Instream Flow Information Paper No. 11, U. S. Department of the Interior, U. S. Fish and Wildlife Service, Cooperative Instream Flow Service Group, Fort Collins, Co.

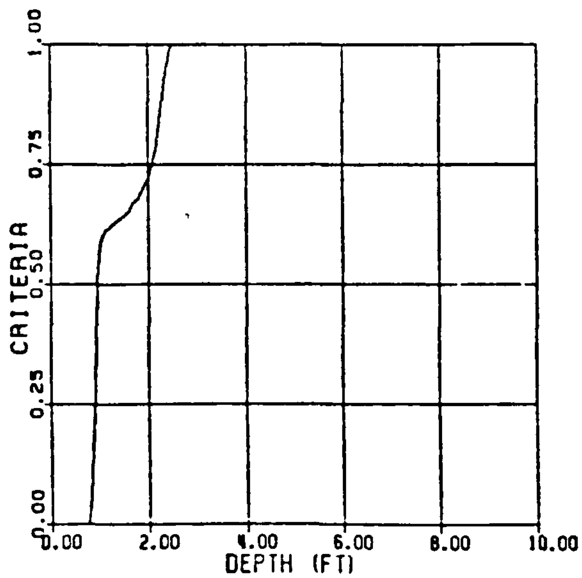
SAS Institute Inc. 1984. SAS User's Guide. Statistical Analysis System Inc., Cary, N. C.

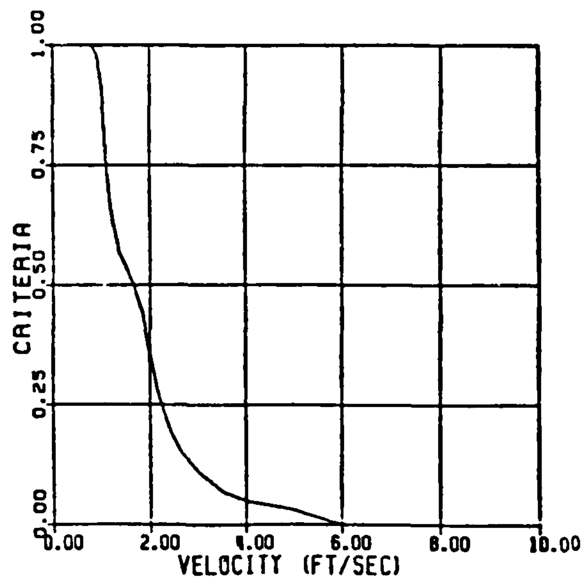
APPENDIX A: SUITABILITY CURVES FOR TROUT LIFE STAGES

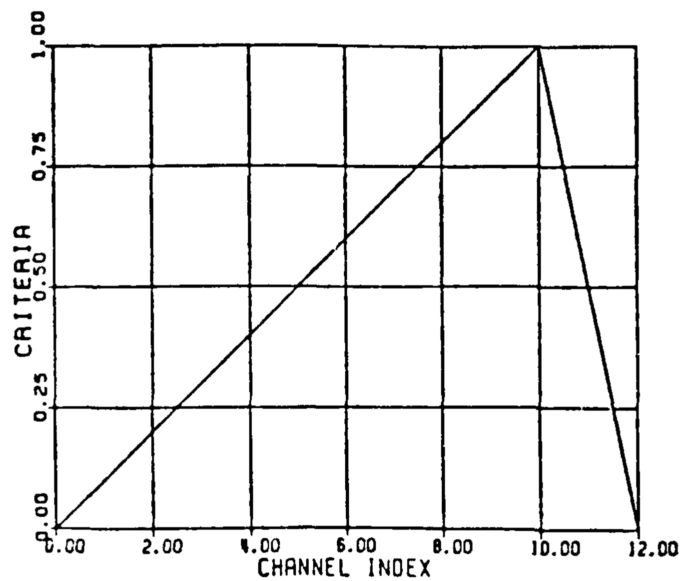
RAINBOW TROUT--ADULT



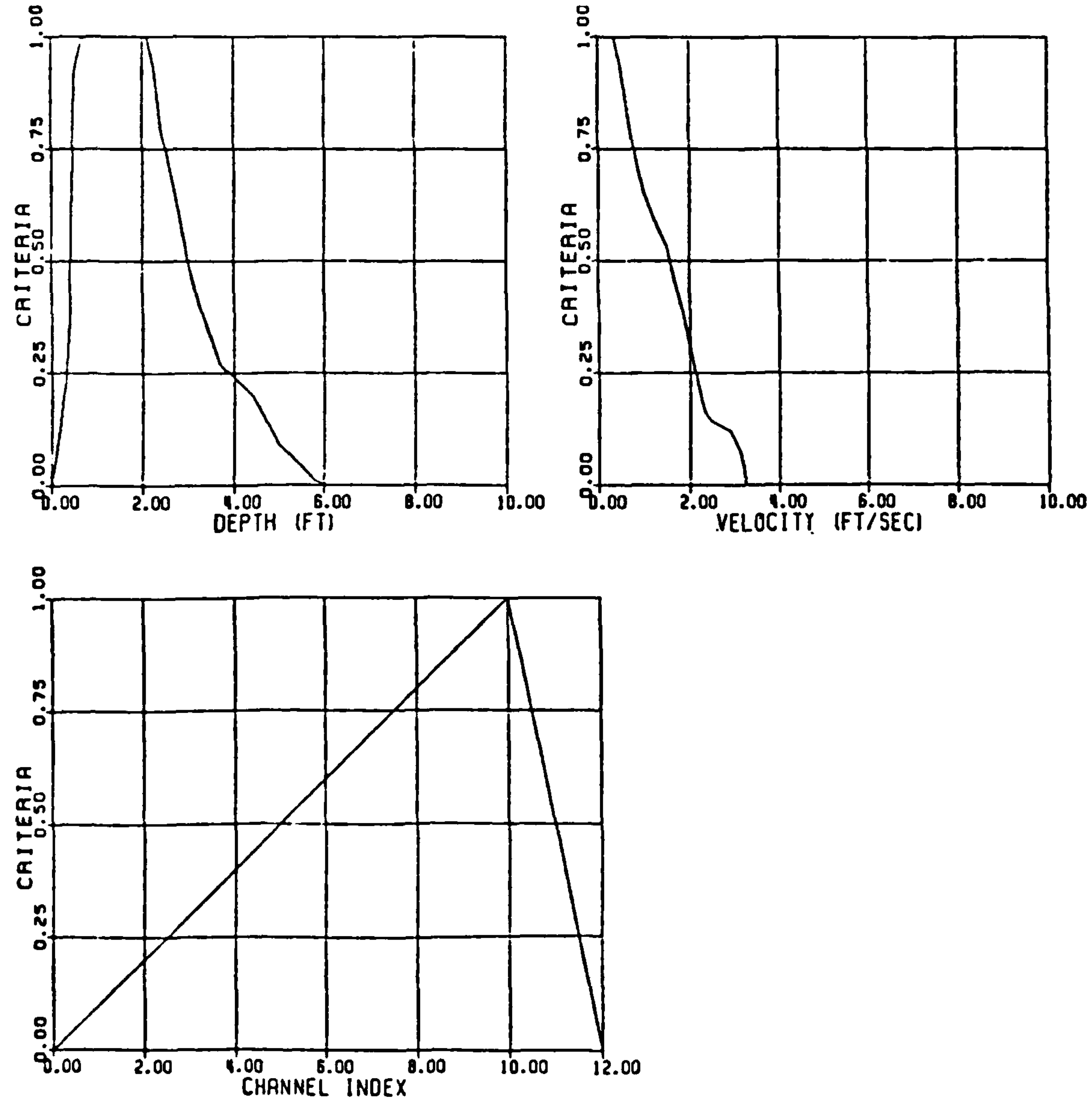
BROWN TROUT--ADULT







BROWN TROUT--JUVENILE



APPENDIX B: CROSS-SECTION PLOTS

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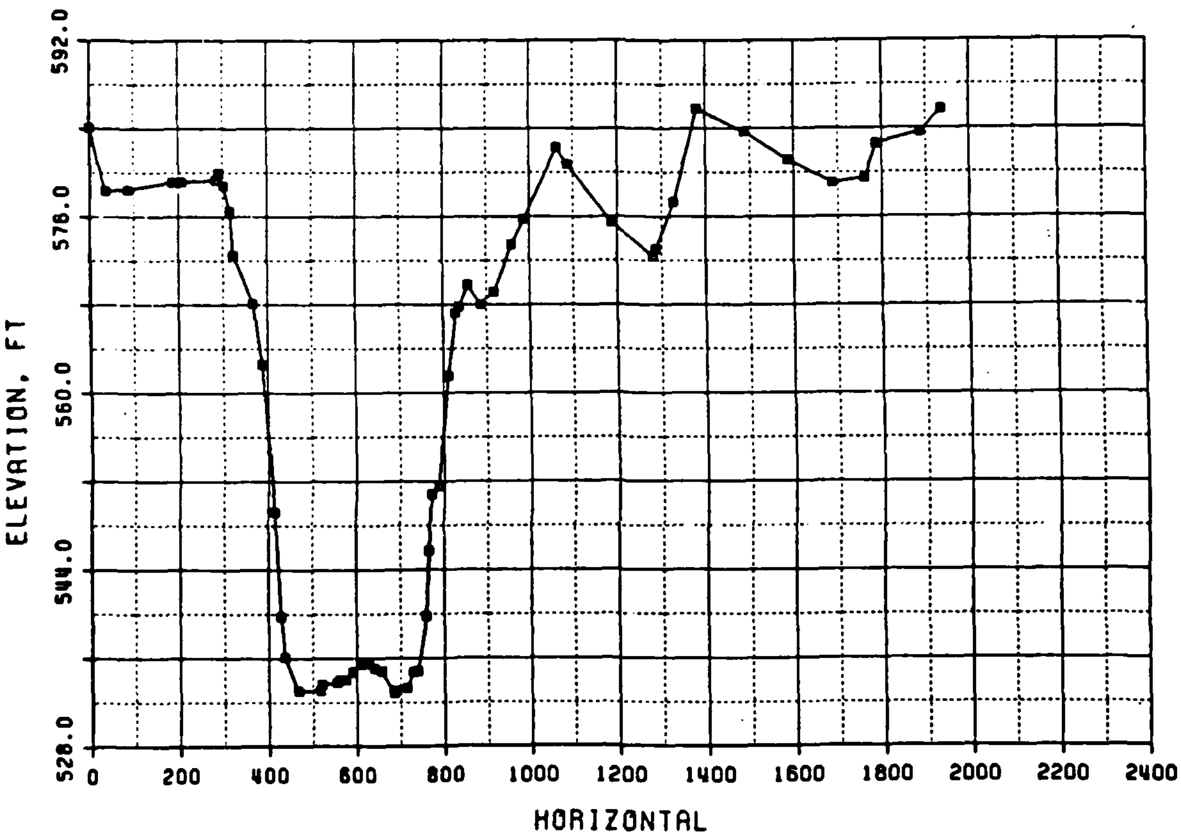

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544.0
528.0
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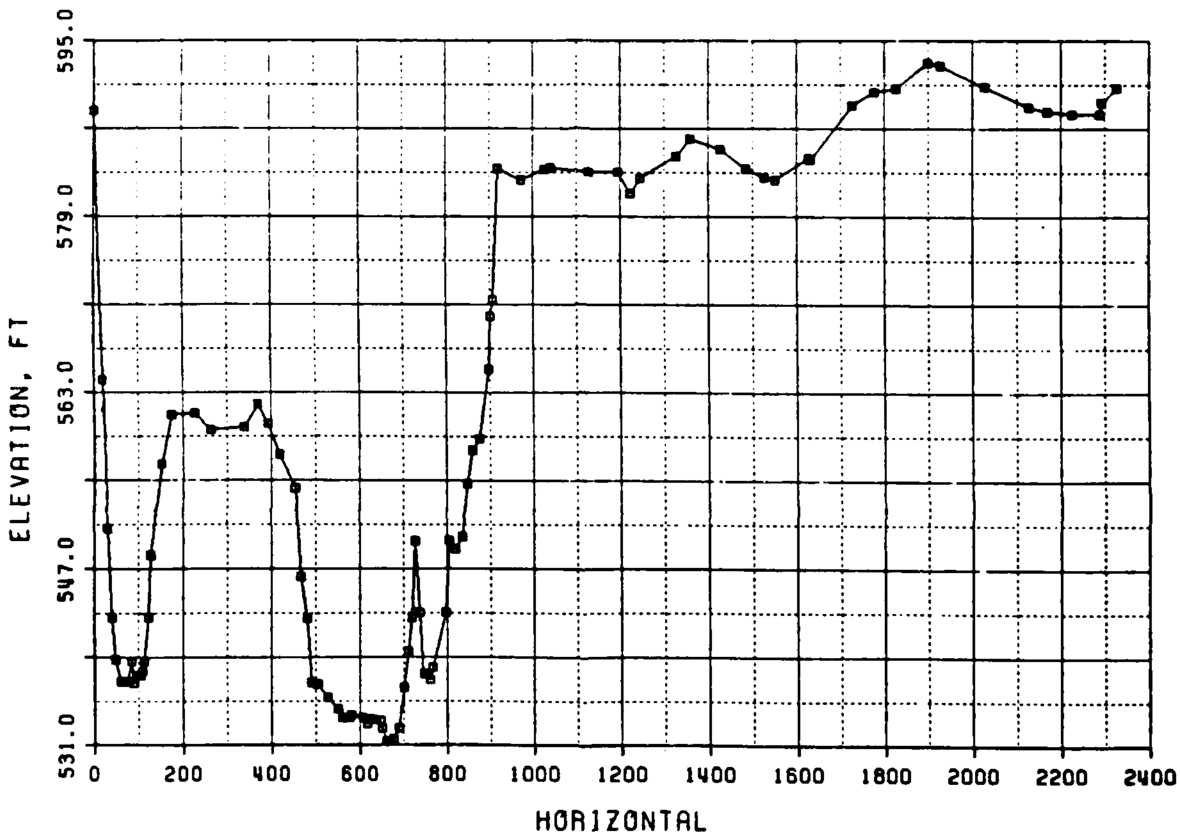
800
1000
1200
1400
1600
1800
2000
2200
2400
HORIZONTAL

X1451.20



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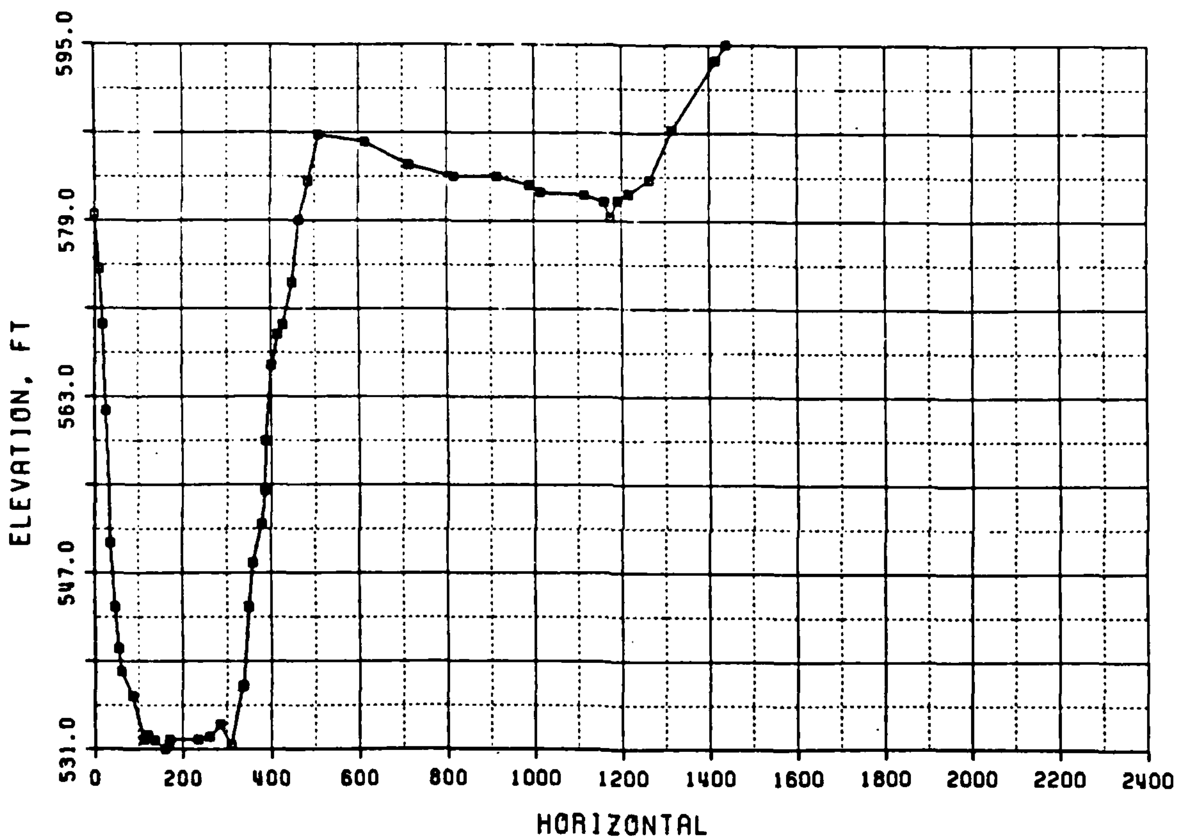
1600
1800
2000
2200
2400
HORIZONTAL

X1451.70



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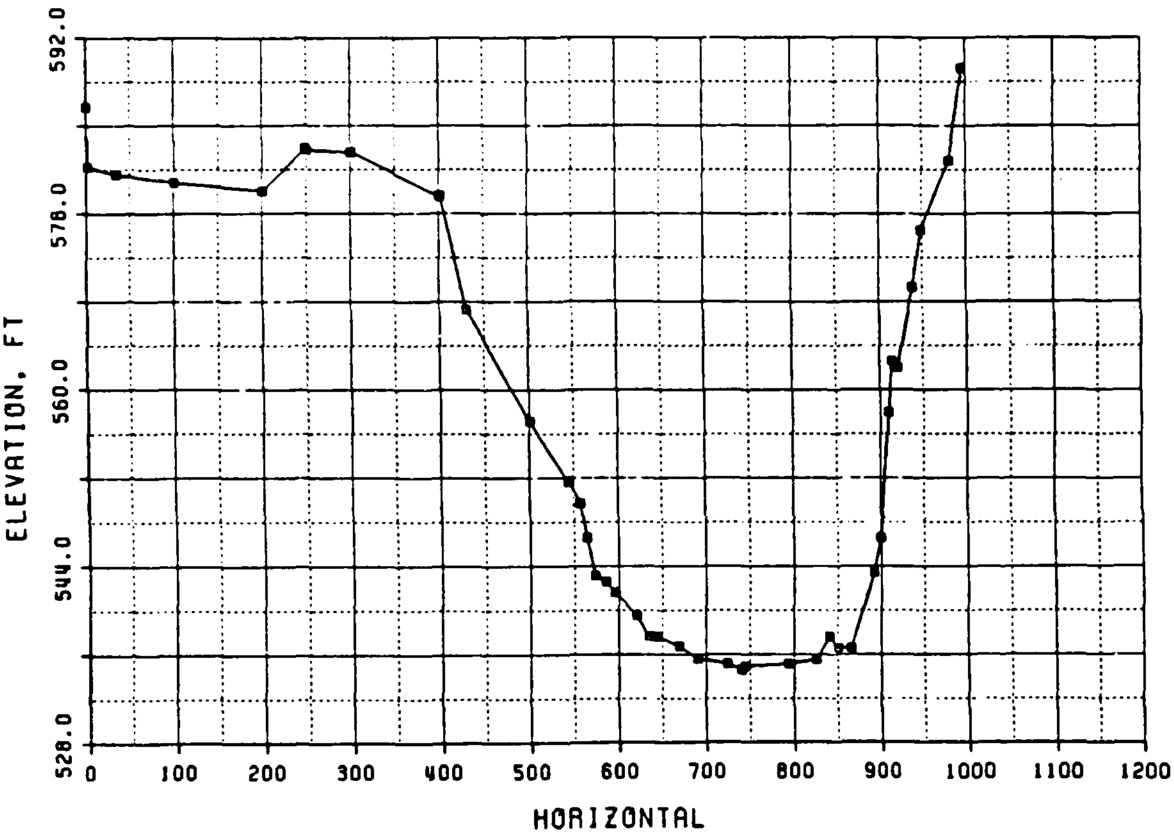

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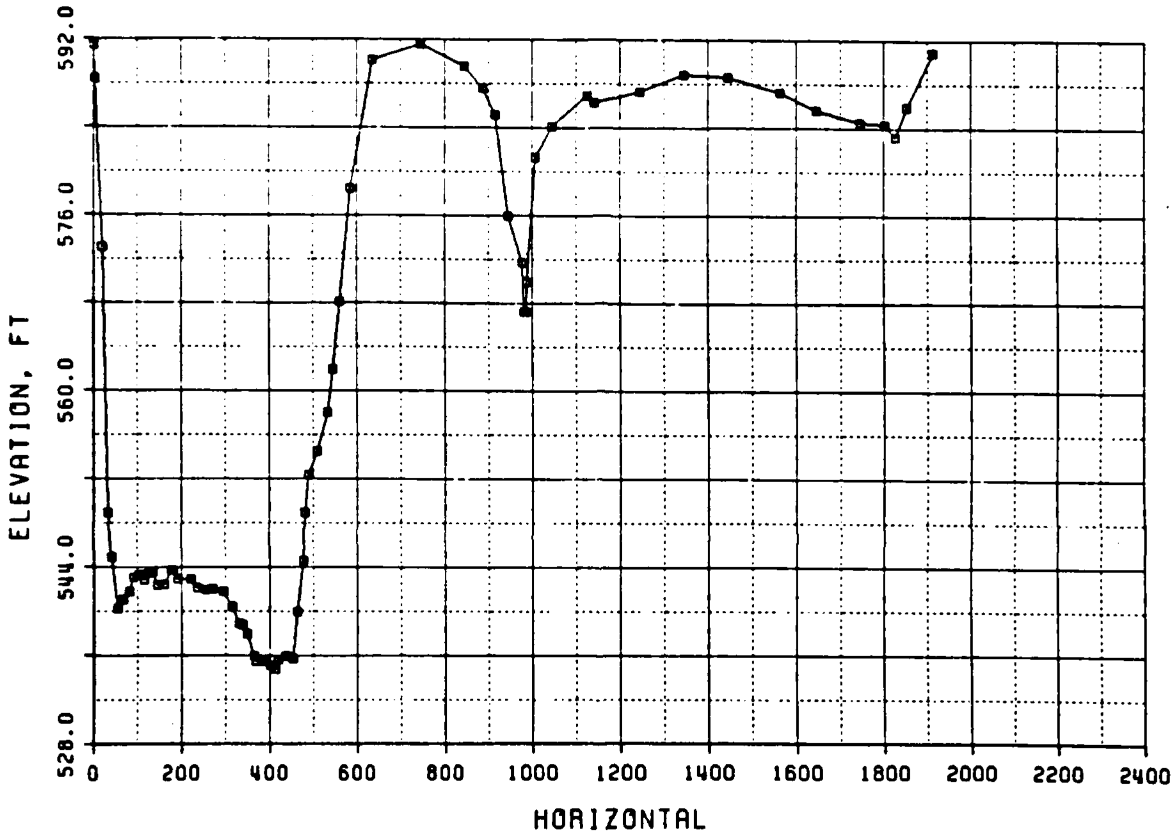

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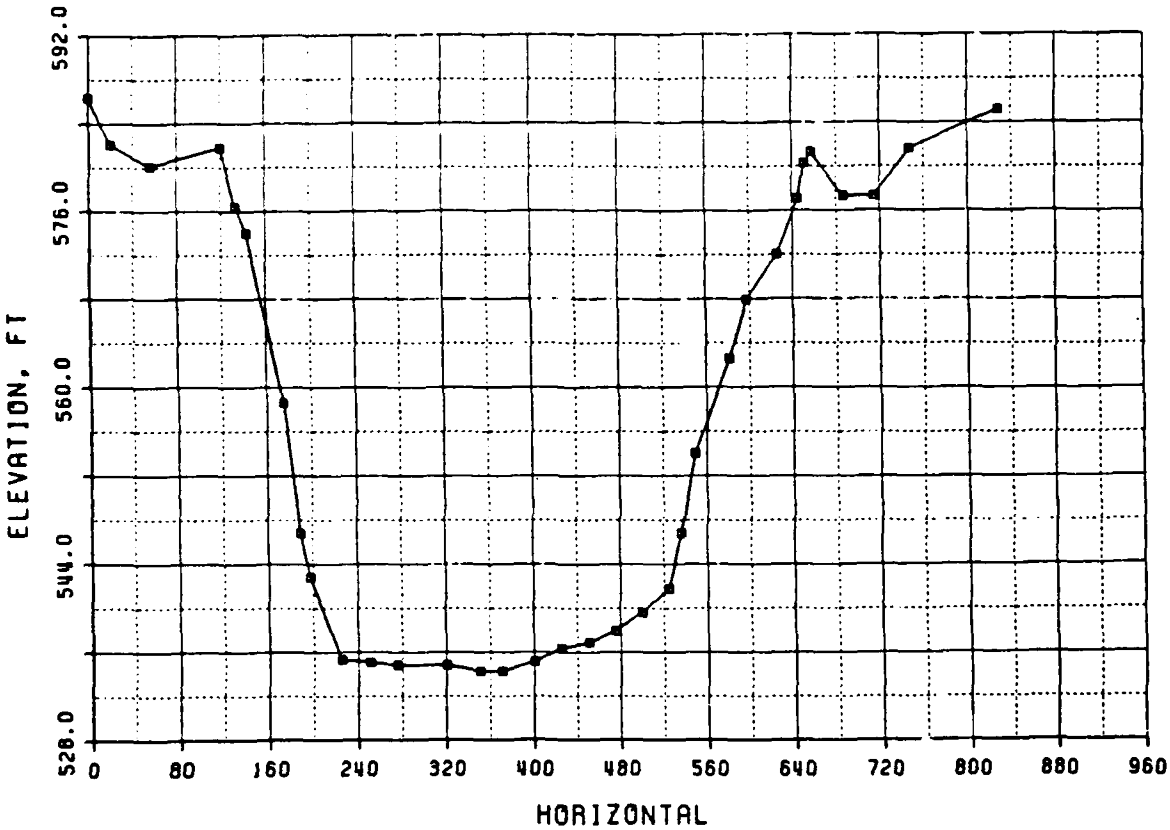

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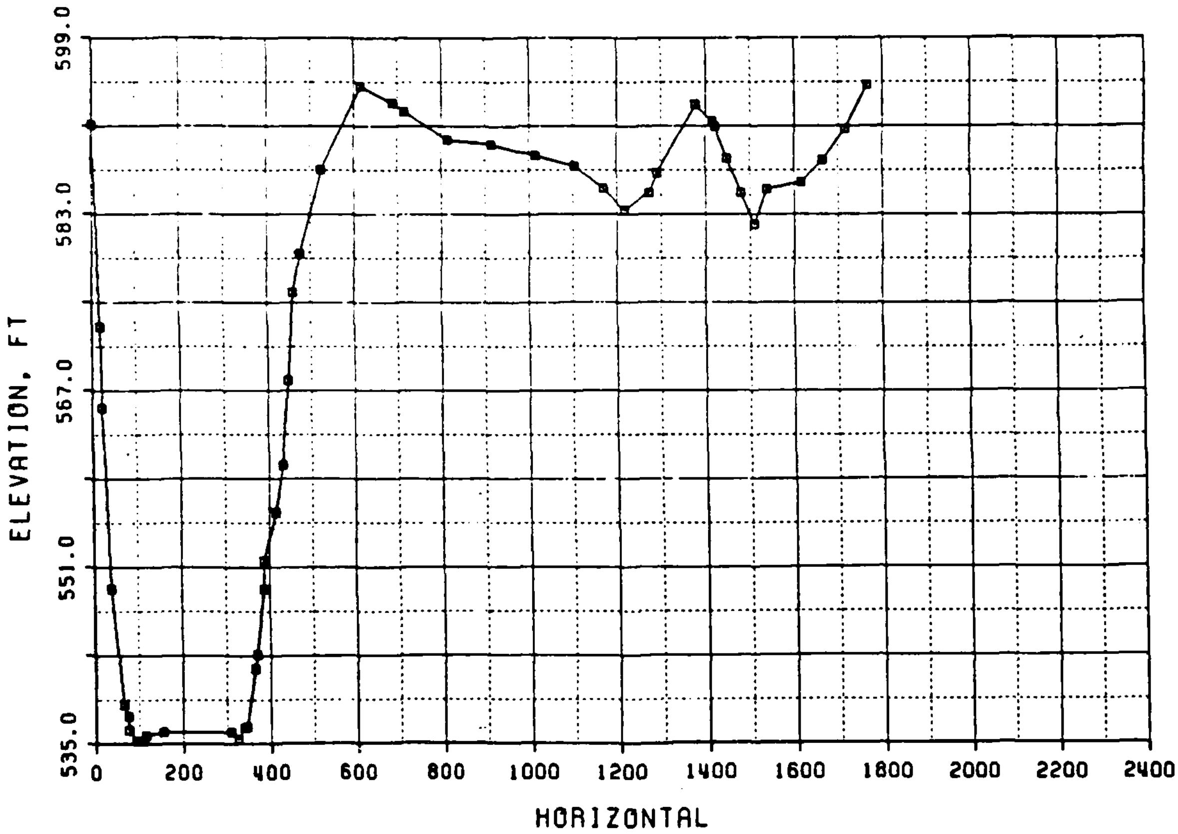
480
560
640
720
800
880
960
HORIZONTAL

X1455.10



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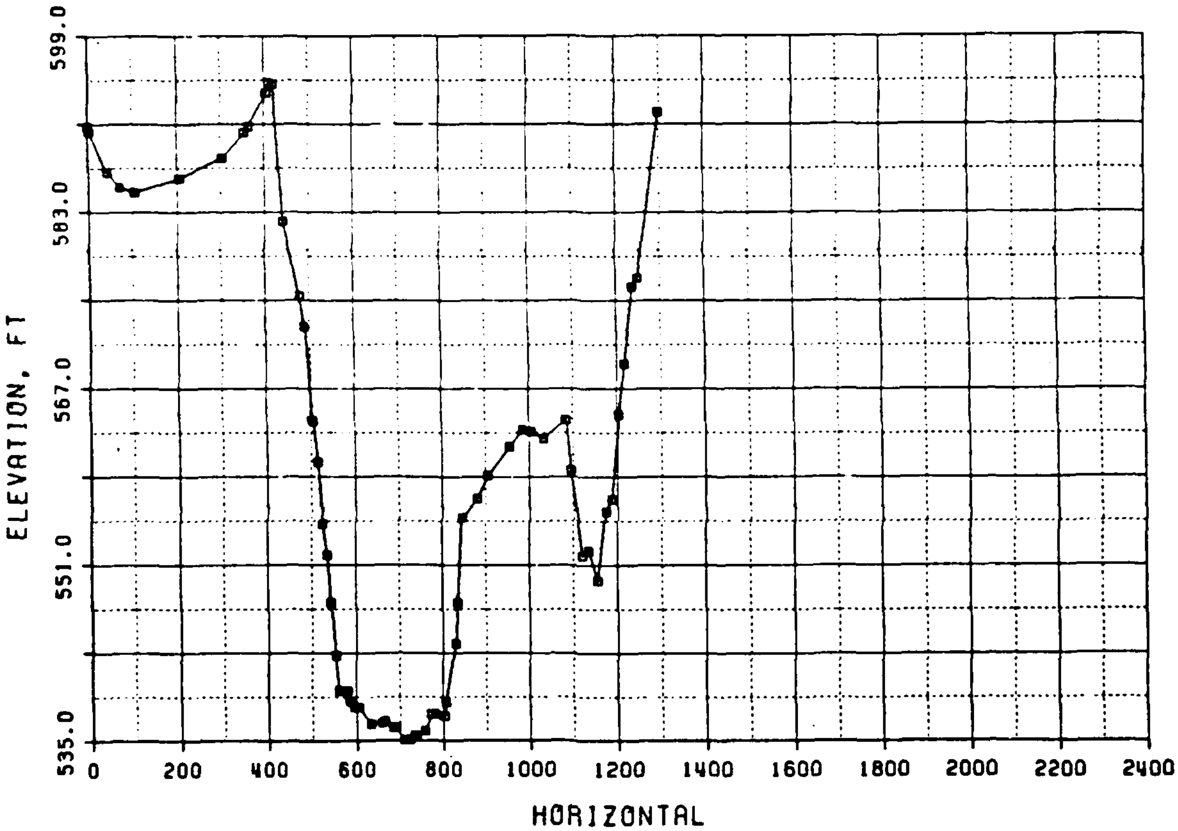
X1455.90



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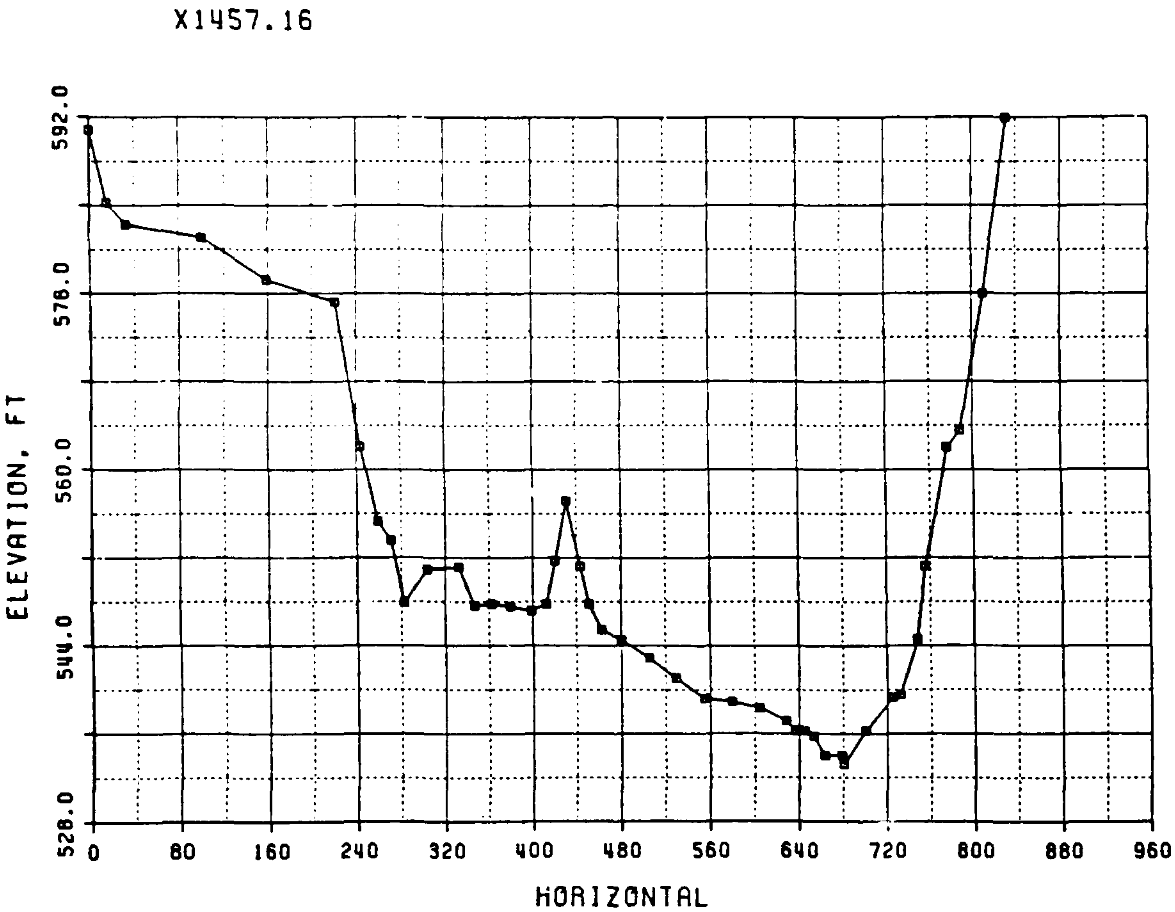
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HORIZONTAL

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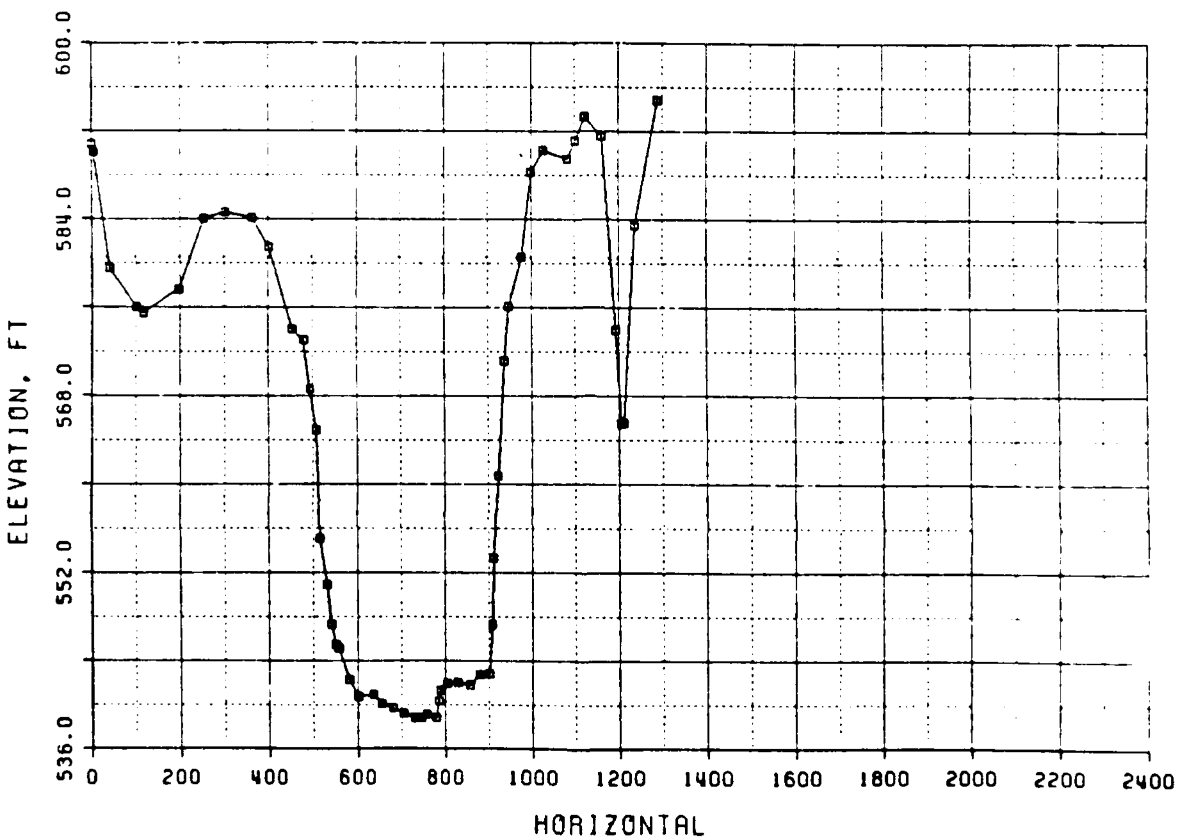
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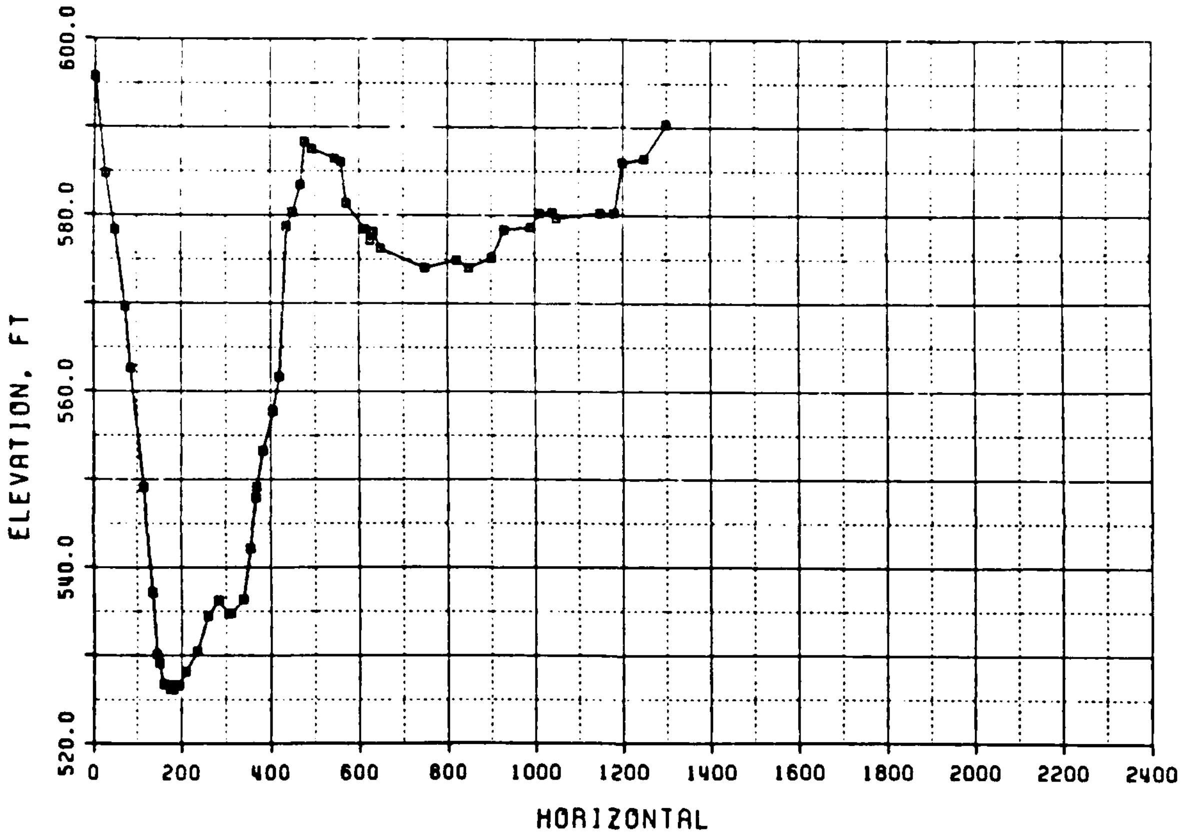

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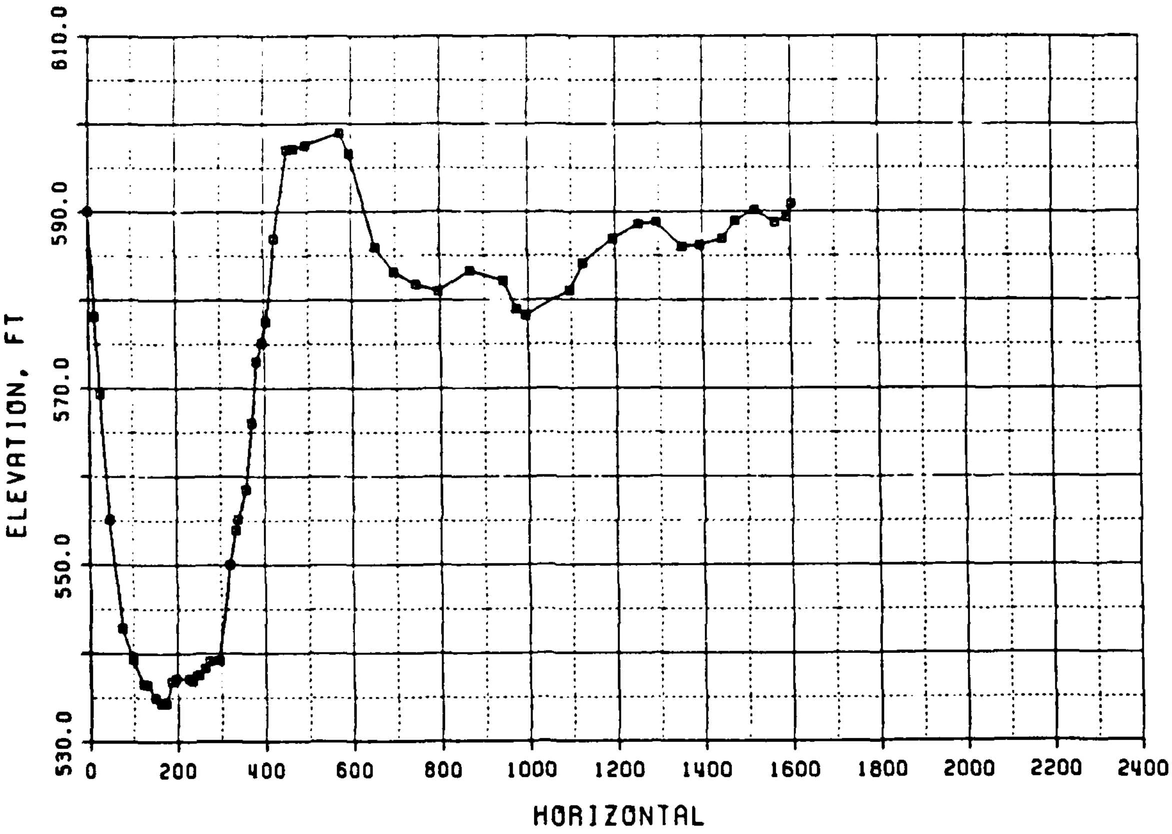
2200
2400
HORIZONTAL

X1460.00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1000
1200
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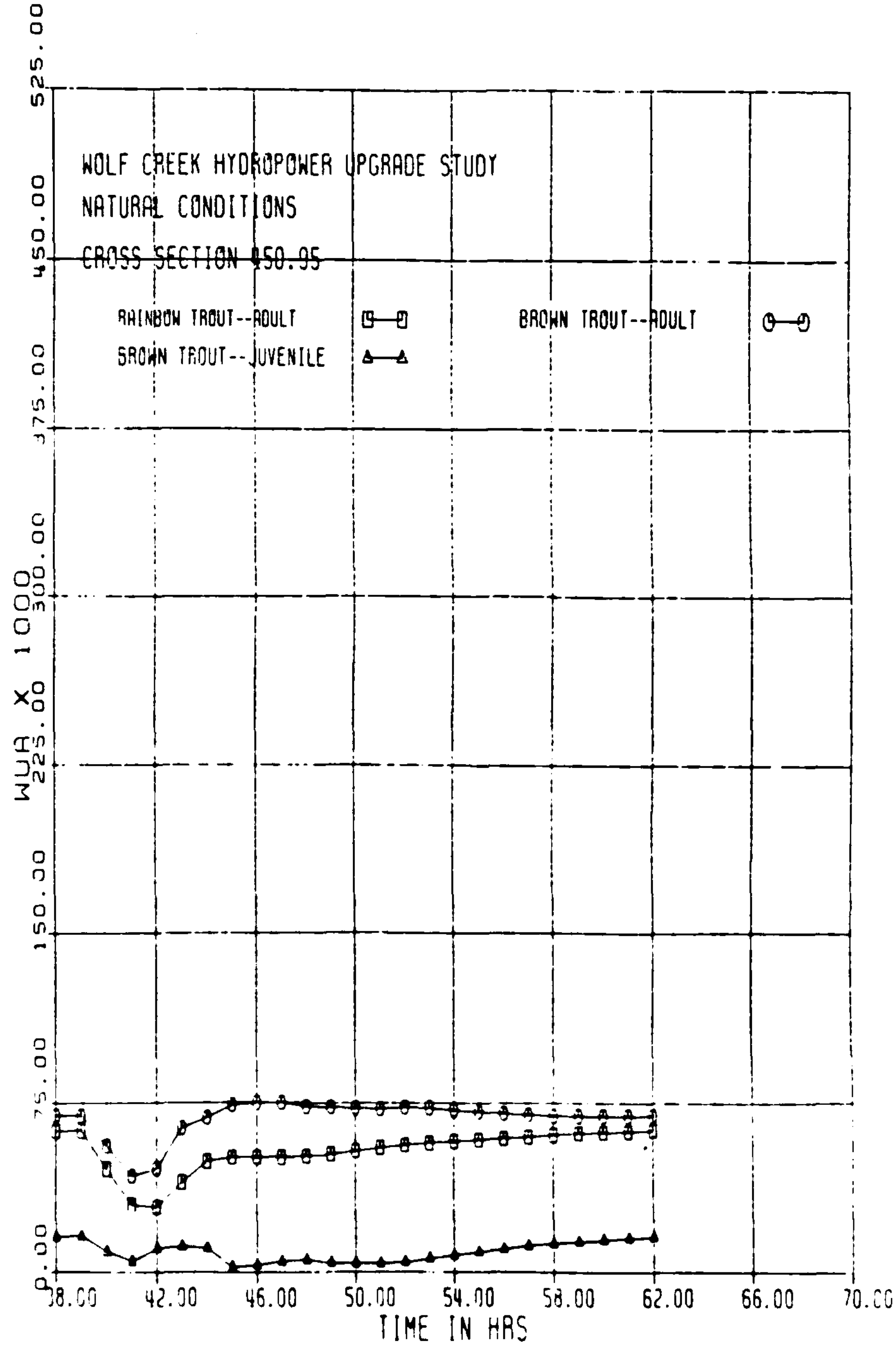
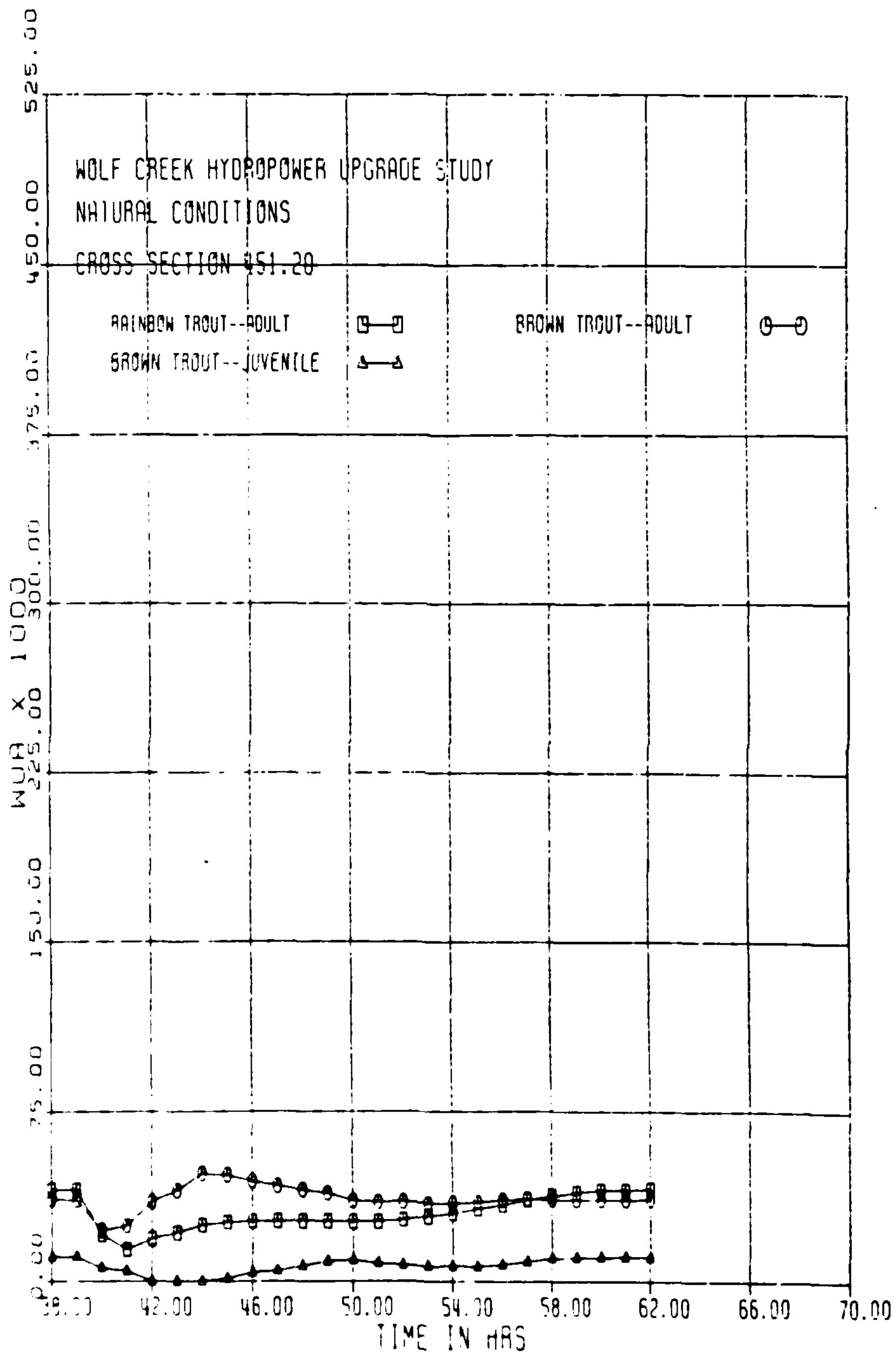
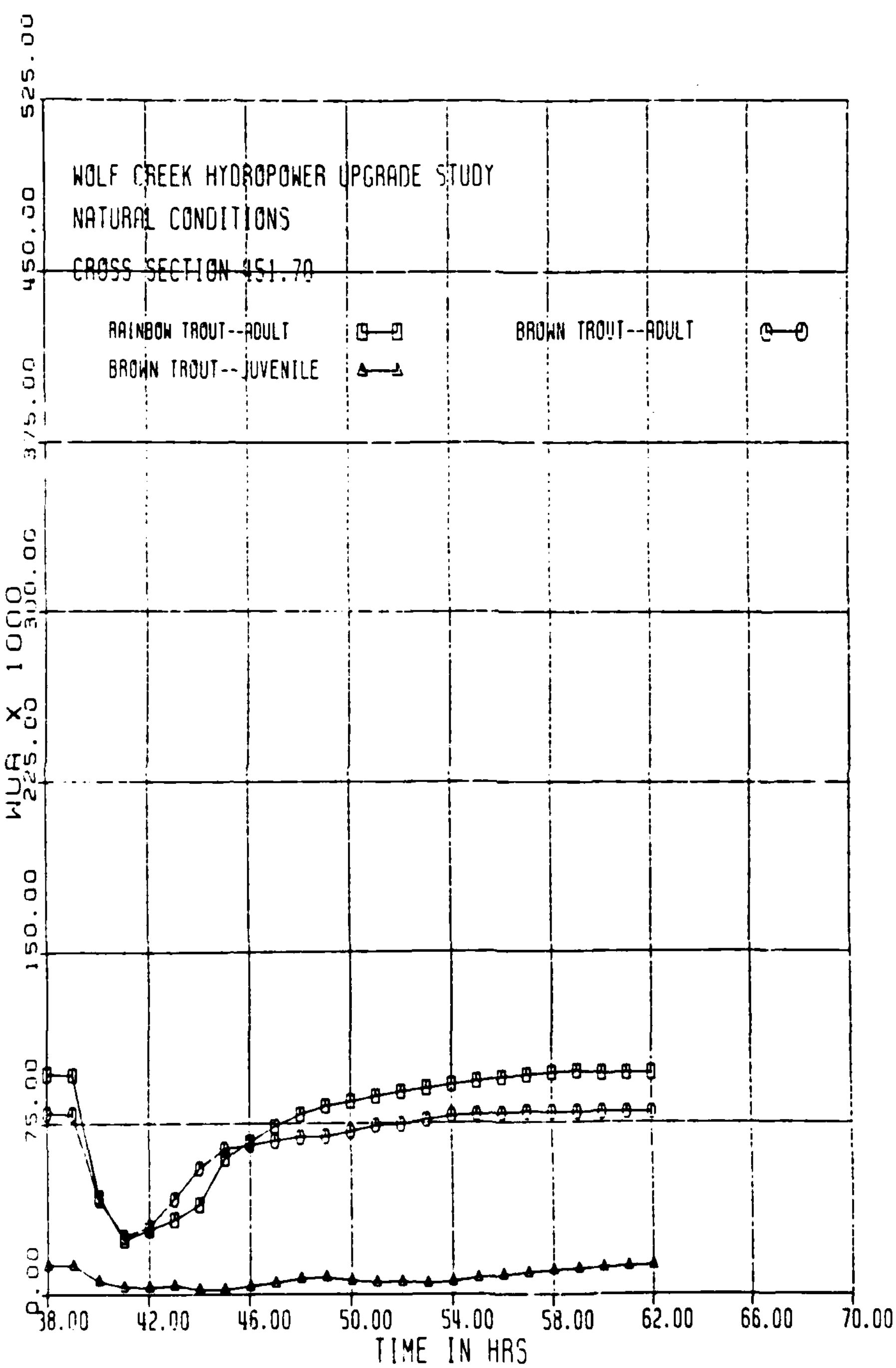
1600
1800
2000
2200
2400
HORIZONTAL

APPENDIX C: WUA VERSUS TIME RELATIONSHIP FOR CROSS SECTIONS UNDER NONREREGULATION (NATURAL) AND REREGULATION CONDITIONS (hour 38 corresponds to 2:00 p.m. Thursday; hour 112 corresponds to 4:00 p.m. Sunday)


WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 450.95
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
TIME IN HRS
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
38.00
42.00
46.00
50.00
54.00
58.00
62.00
66.00
70.00


WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 451.20
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
TIME IN HRS
525.00
450.00
375.00
300.00
225.00
150.00
75.00
0.00
42.00
46.00
50.00
54.00
58.00
62.00
66.00
70.00


WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 451.70
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BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
38.00
42.00
46.00
50.00
54.00
58.00
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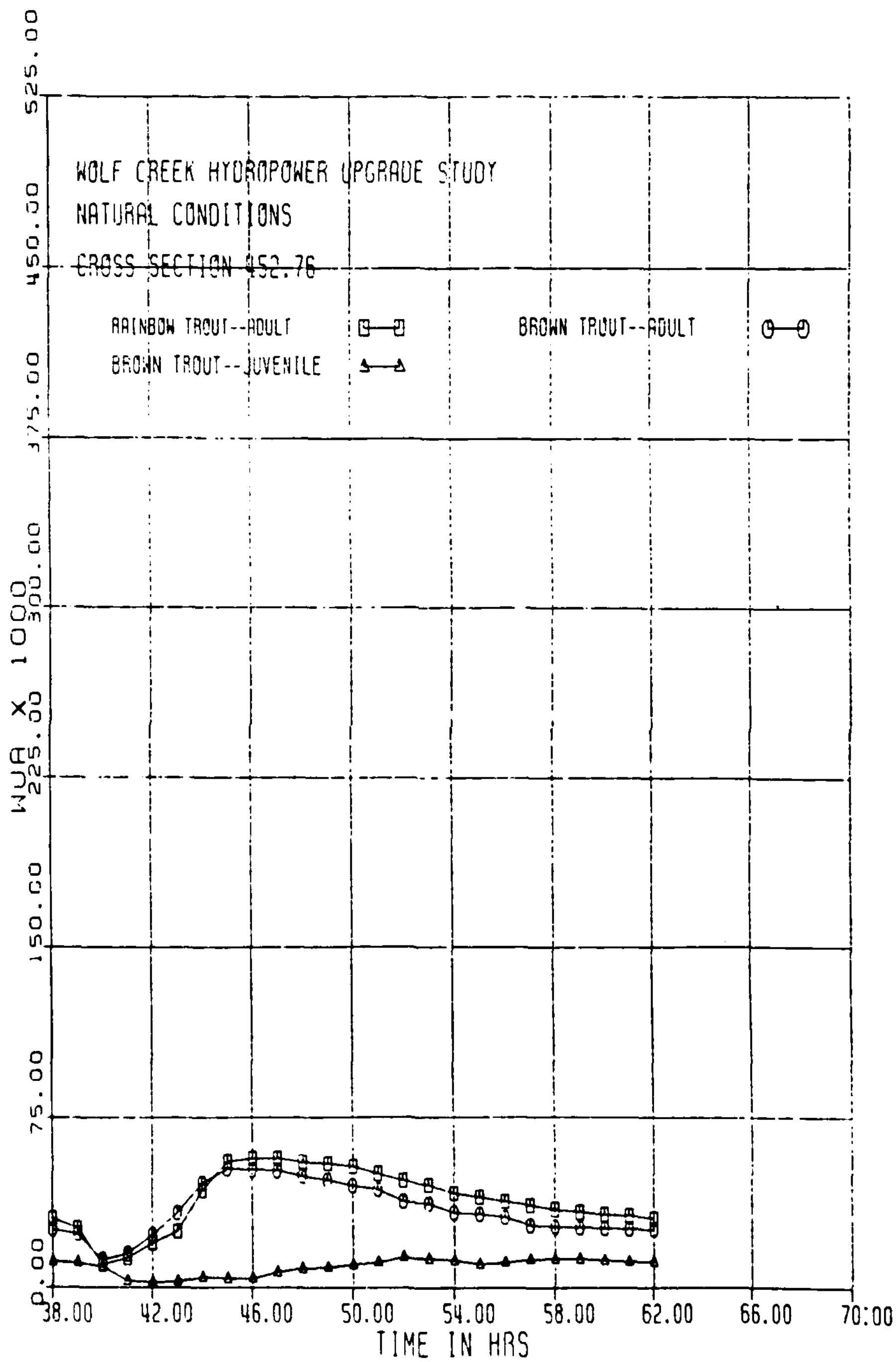
66.00
70.00
TIME IN HRS


WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 452.76
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
38.00
42.00
46.00
50.00
54.00
58.00
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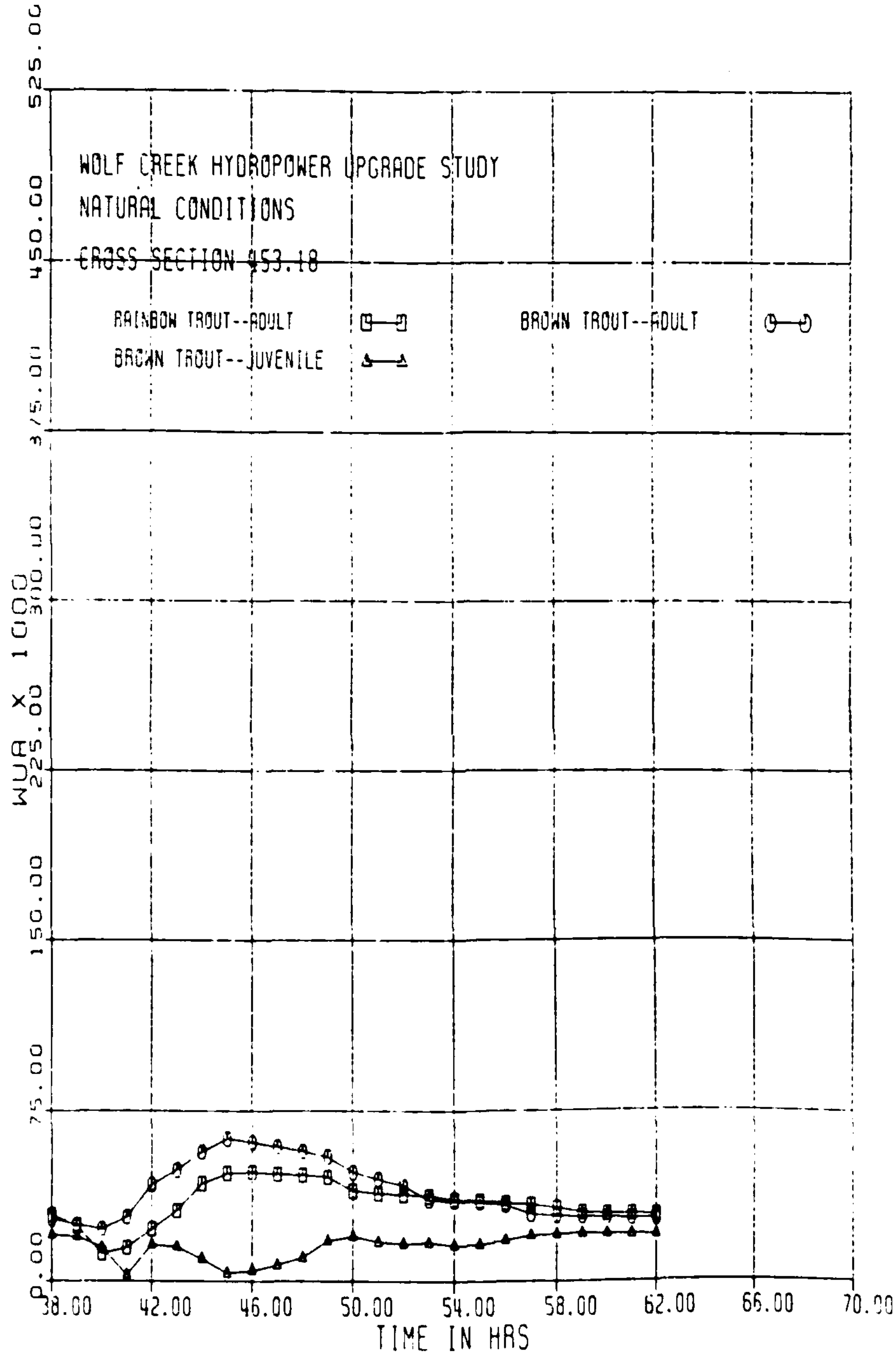
66.00
70.00
TIME IN HRS


WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 453.18
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BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
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150.00
225.00
300.00
375.00
450.00
525.00
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42.00
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50.00
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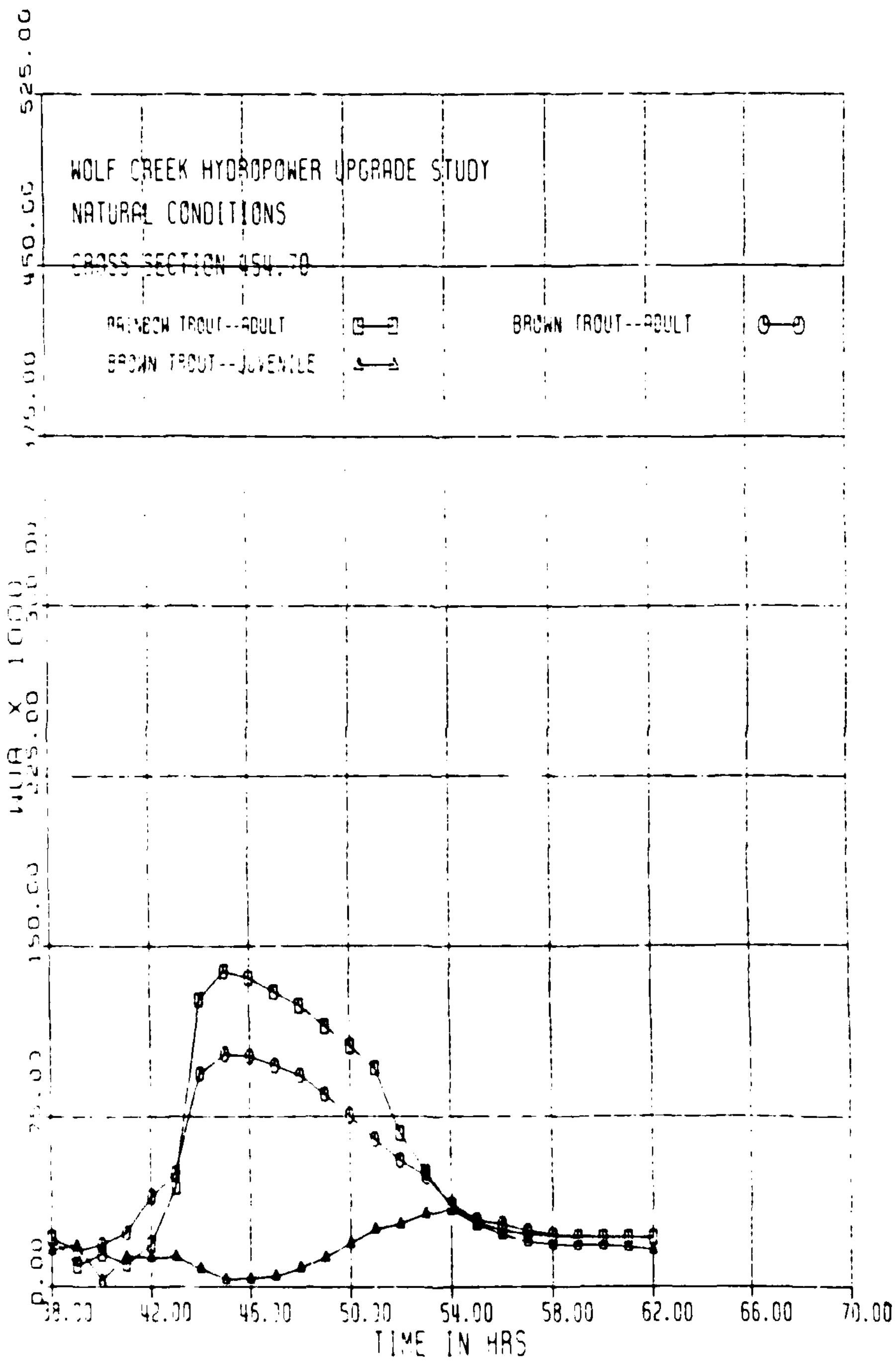
66.00
70.00
TIME IN HRS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NATURAL CONDITIONS
CROSS SECTION 454.70
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BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
TIME IN HRS
0.00
75.00
150.00
225.00
300.00
375.00
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38.00
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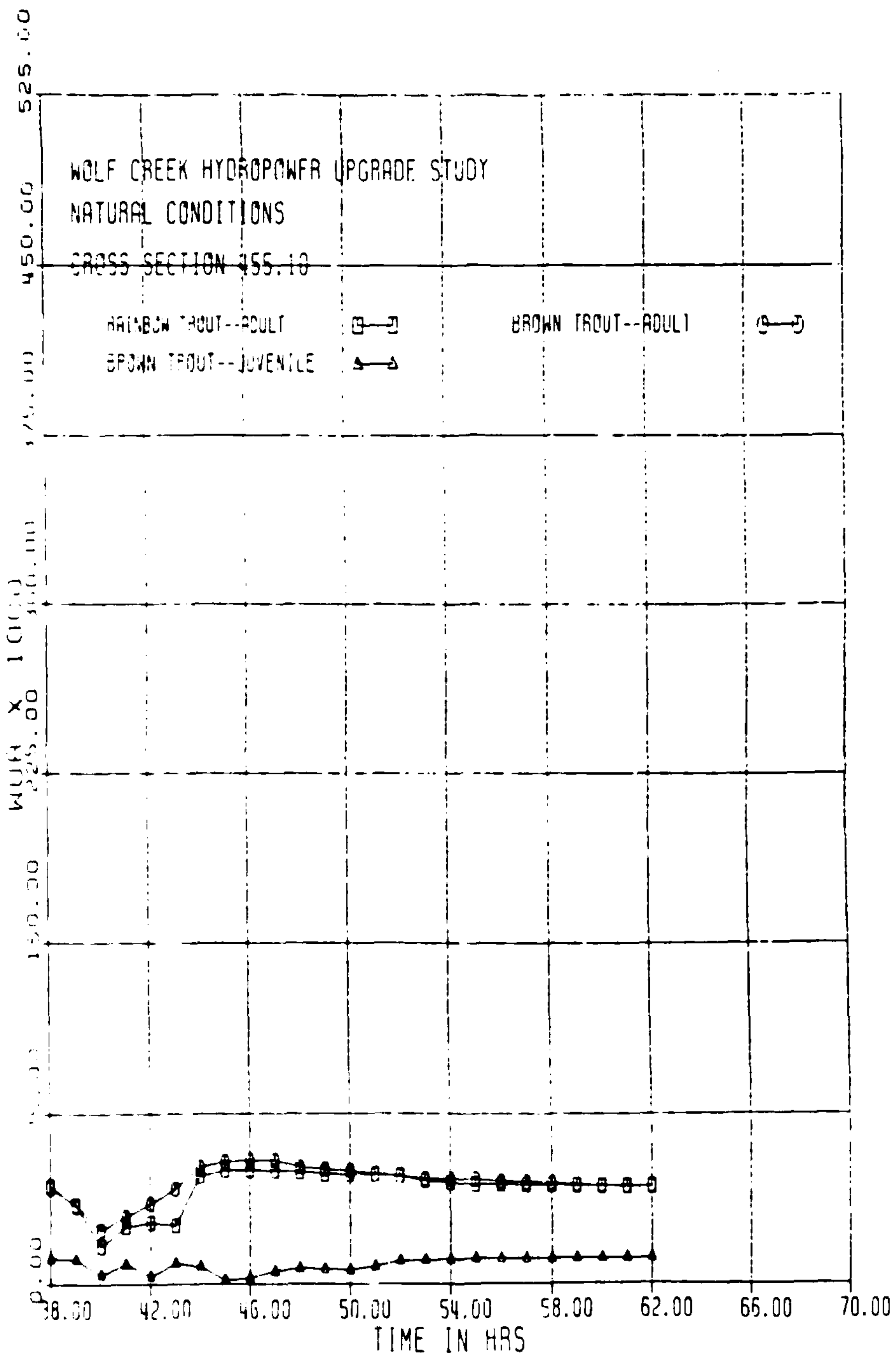
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NATURAL CONDITIONS
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BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
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450.00
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42.00
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50.00
54.00
58.00
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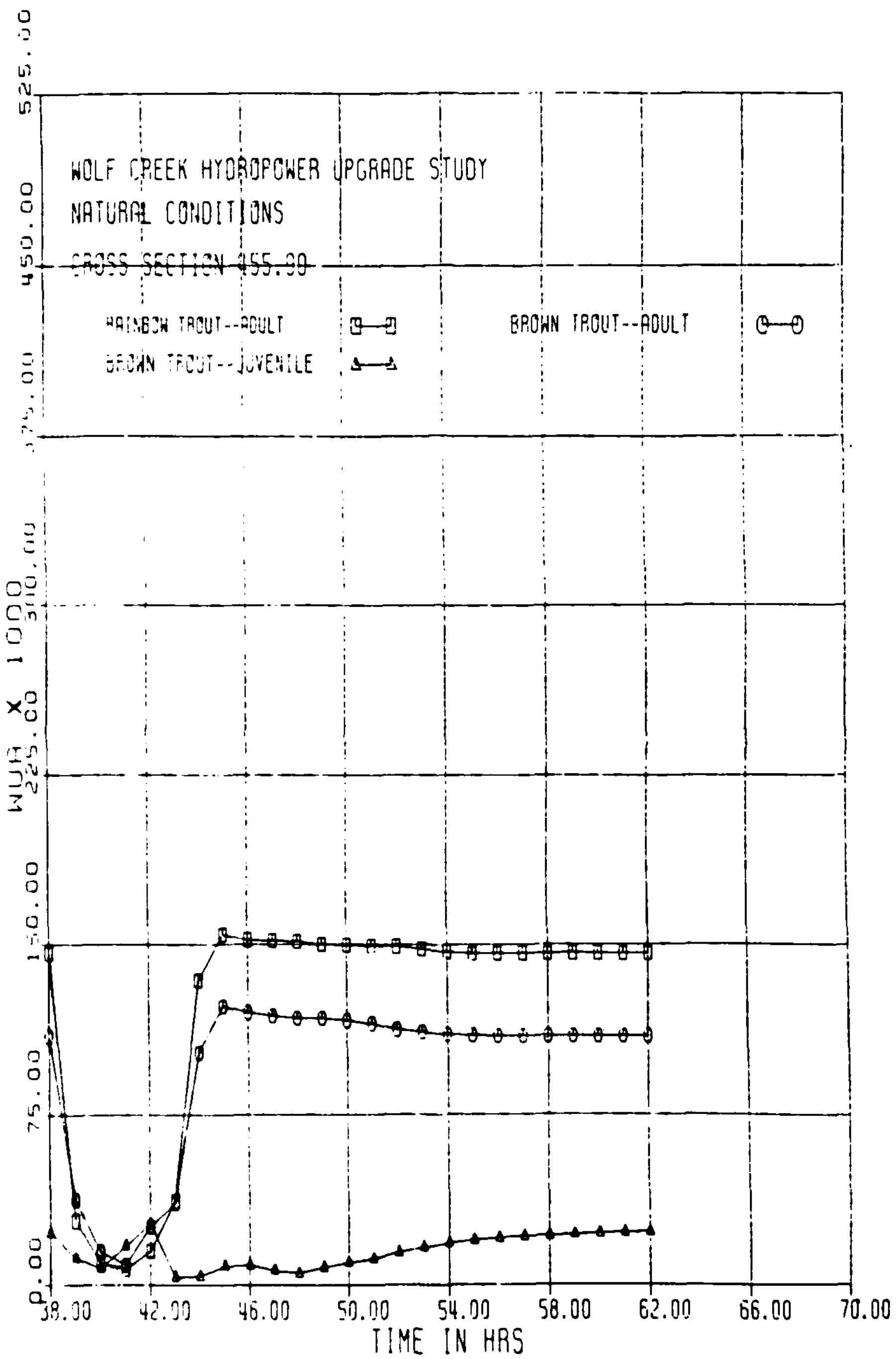
TIME IN HRS



WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 455.00
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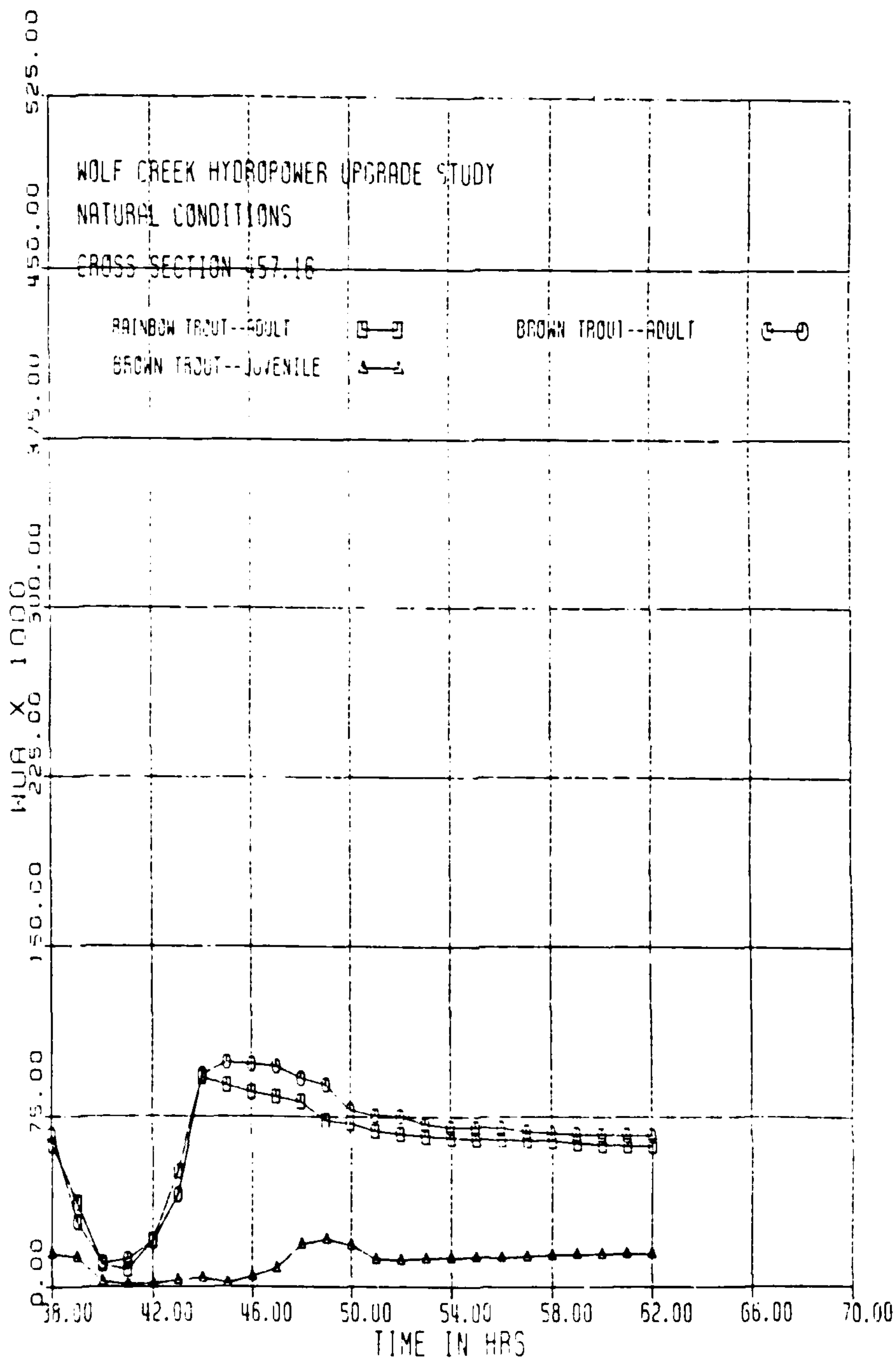
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
TIME IN HRS
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
38.00
42.00
46.00
50.00
54.00
58.00
62.00
66.00
70.00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BROWN TROUT--JUVENILE
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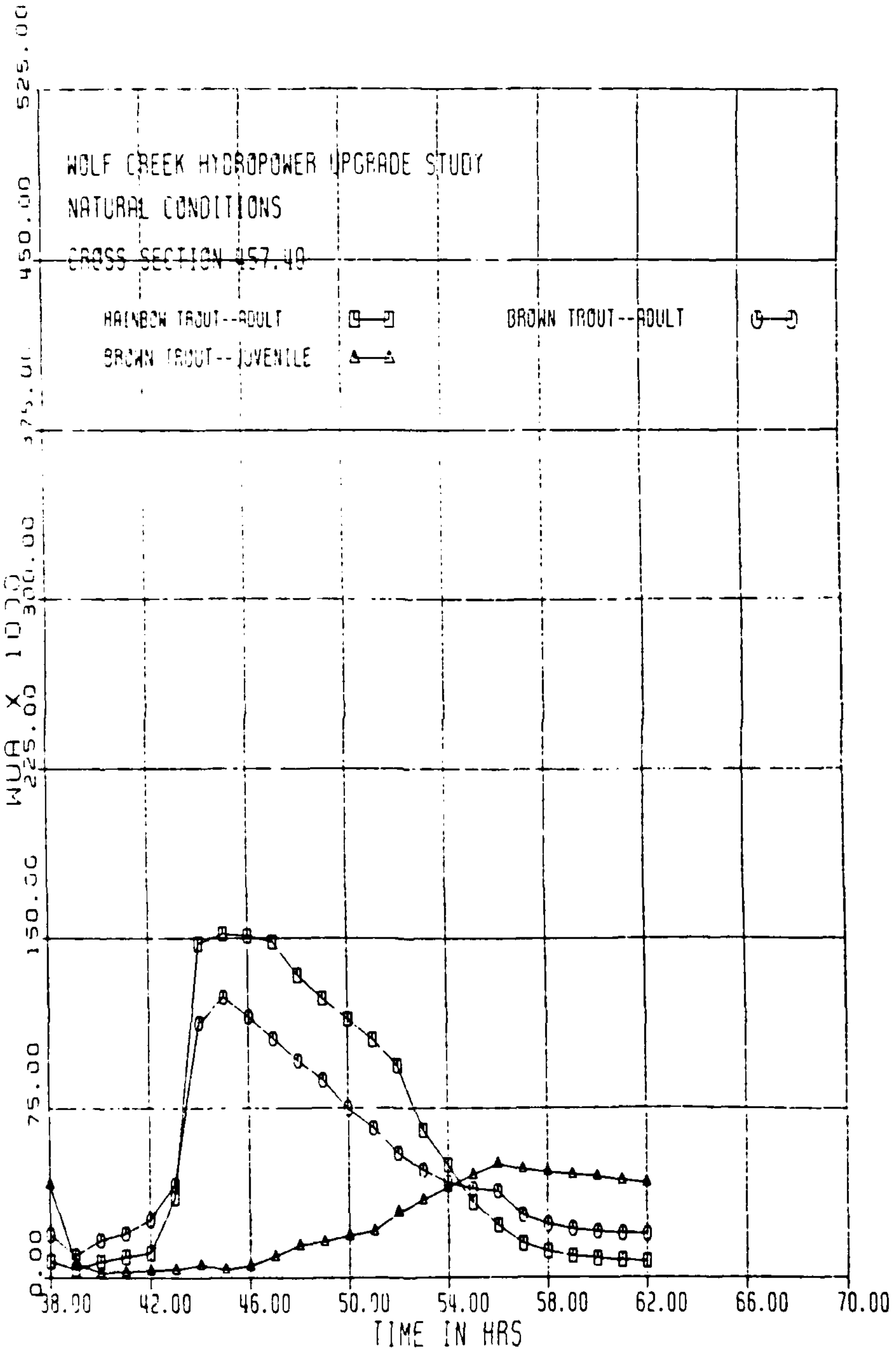
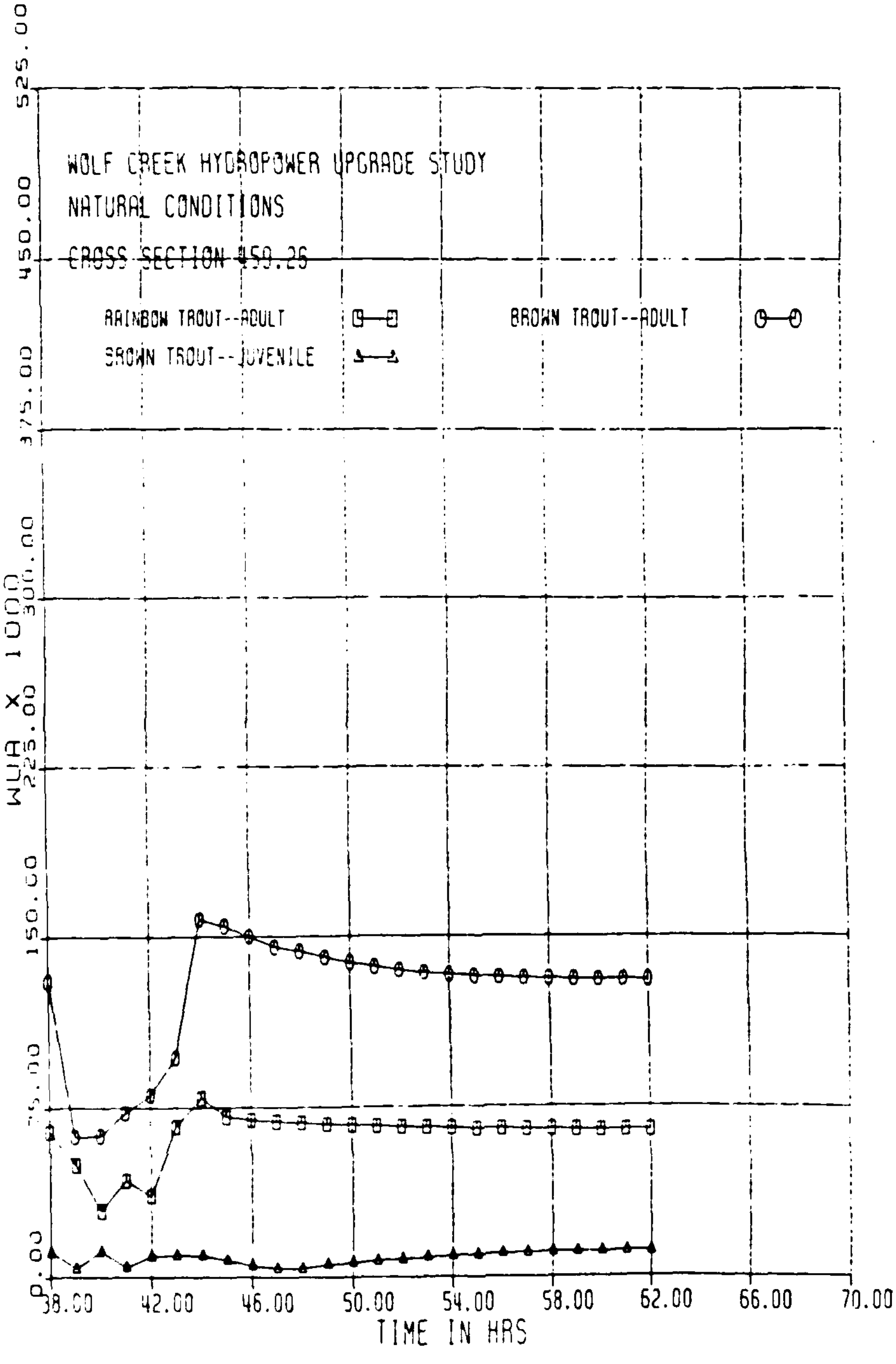
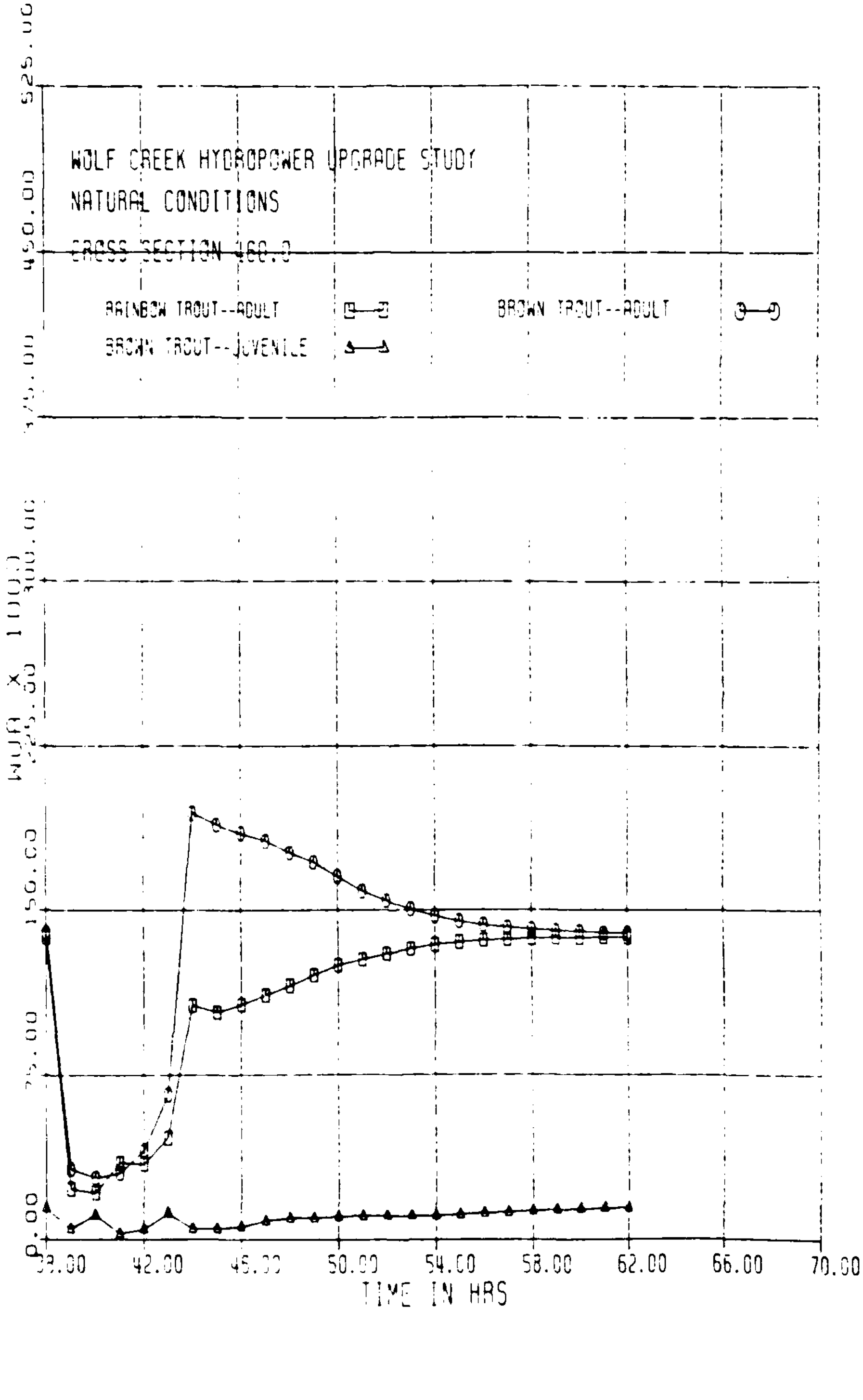
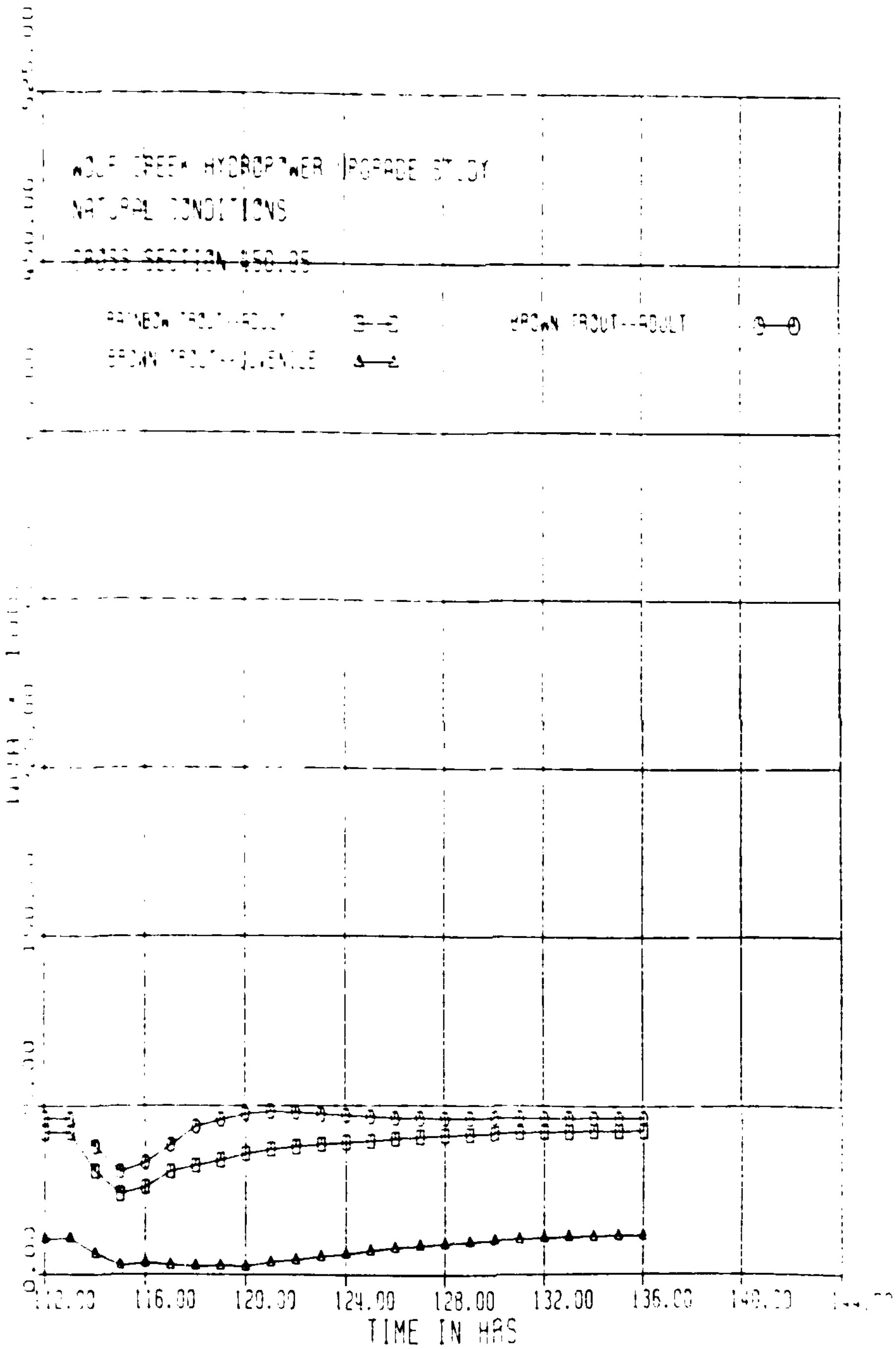
150.00
225.00
300.00
375.00
450.00
525.00
38.00
42.00
46.00
50.00
54.00
58.00
62.00
66.00
70.00
TIME IN HRS


WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 457.40
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
38.00
42.00
46.00
50.00
54.00
58.00
62.00
66.00
70.00
TIME IN HRS


WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 459.26
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
38.00
42.00
46.00
50.00
54.00
58.00
62.00
66.00
70.00
TIME IN HRS

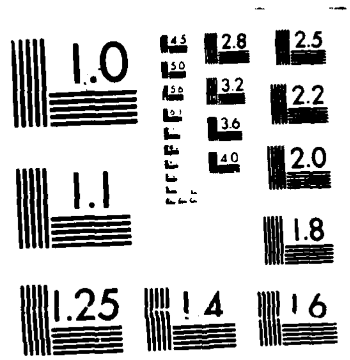

WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 460.0
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
TIME IN HRS
42.00
50.00
54.00
58.00
62.00
66.00
70.00
525.00
450.00
150.00
0.00



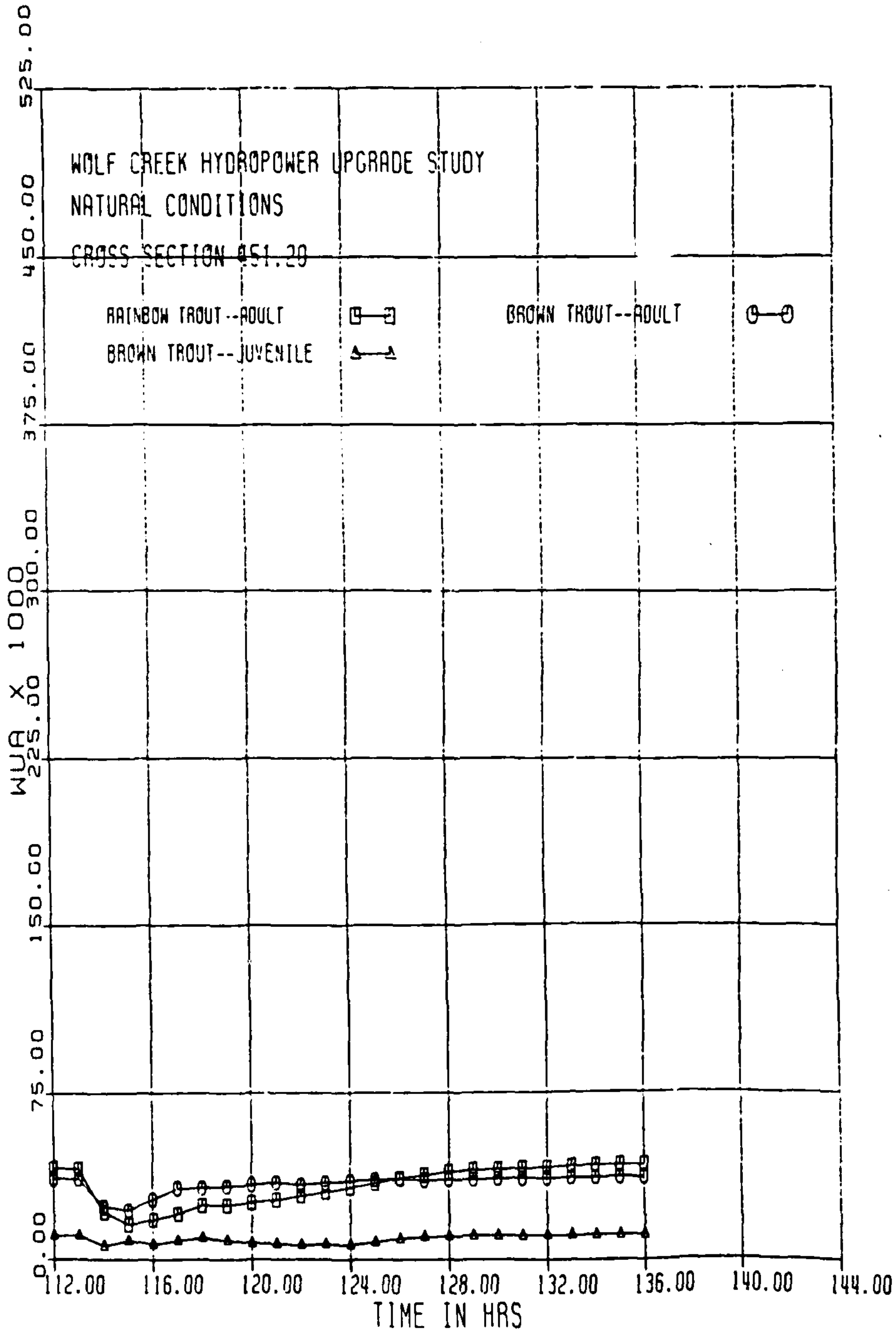
TIME IN HRS

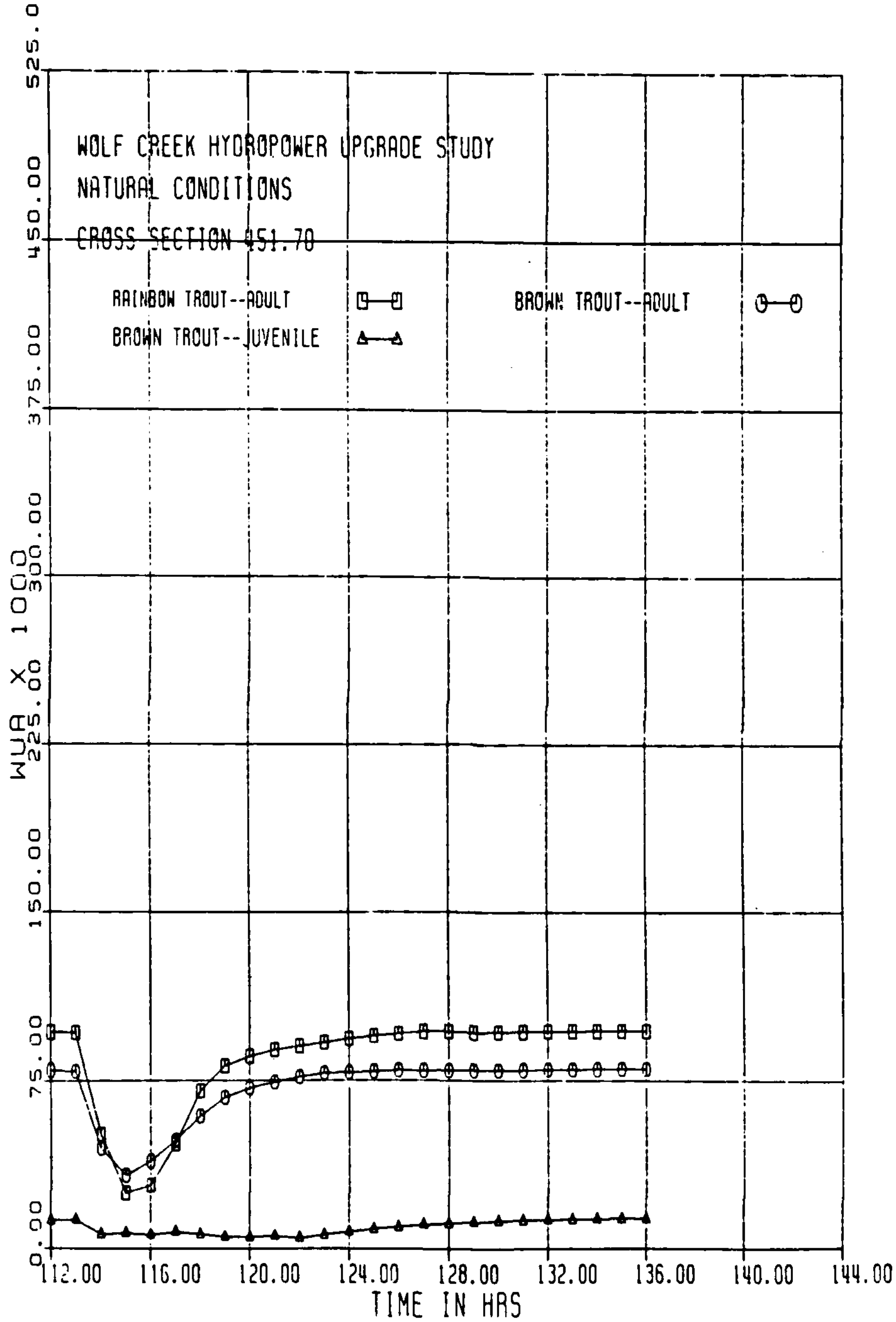
AD-A179 787 COMPARATIVE EFFECTS ON TROUT HABITAT OF HYDROPOWER MODIFICATION WITH AND W. (U) ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS ENVIR. 2/2

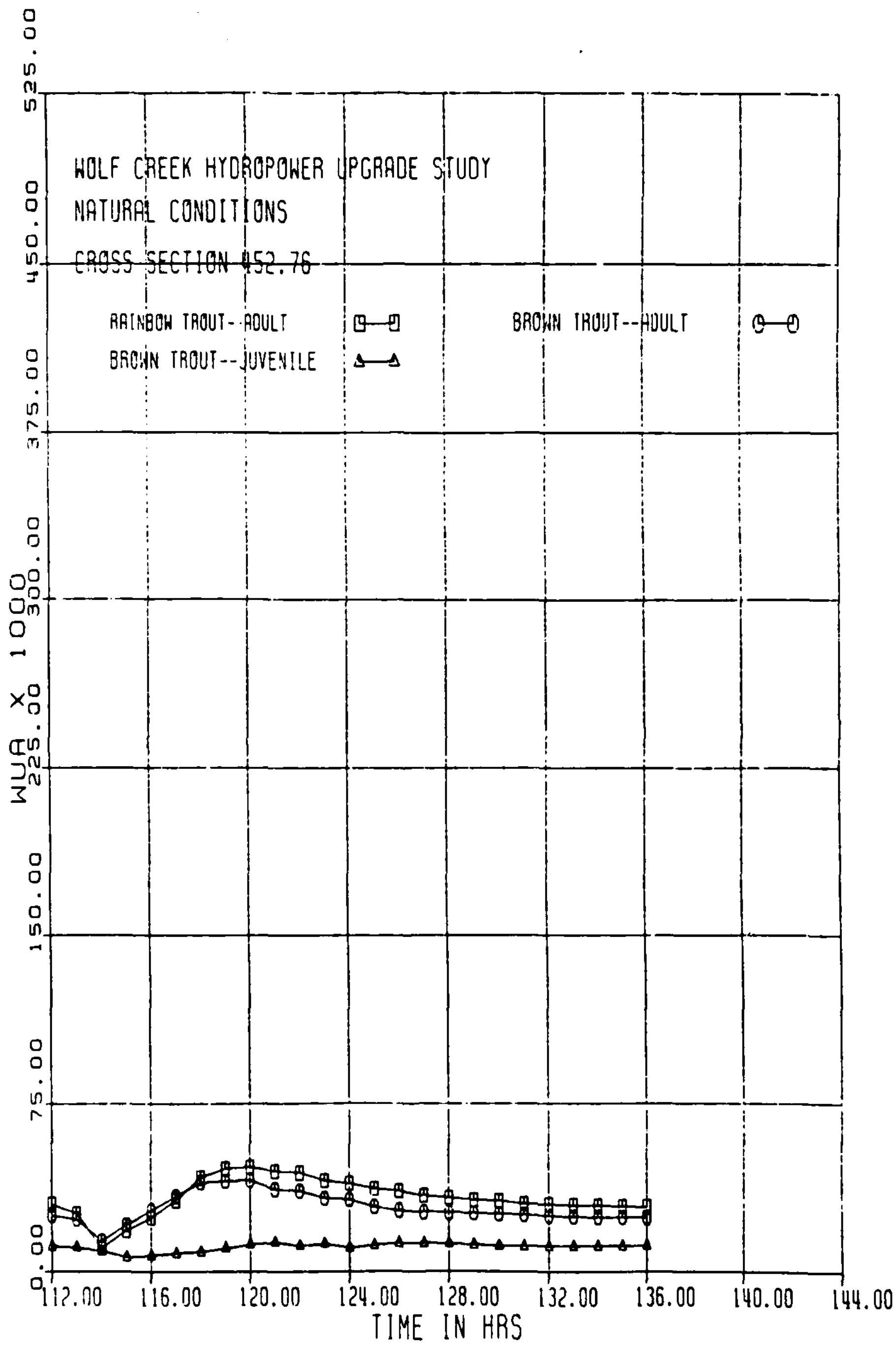
UNCLASSIFIED L T CURTIS ET AL. MAR 87 WES/MP/EL-87-2 F/G 6/6 NL



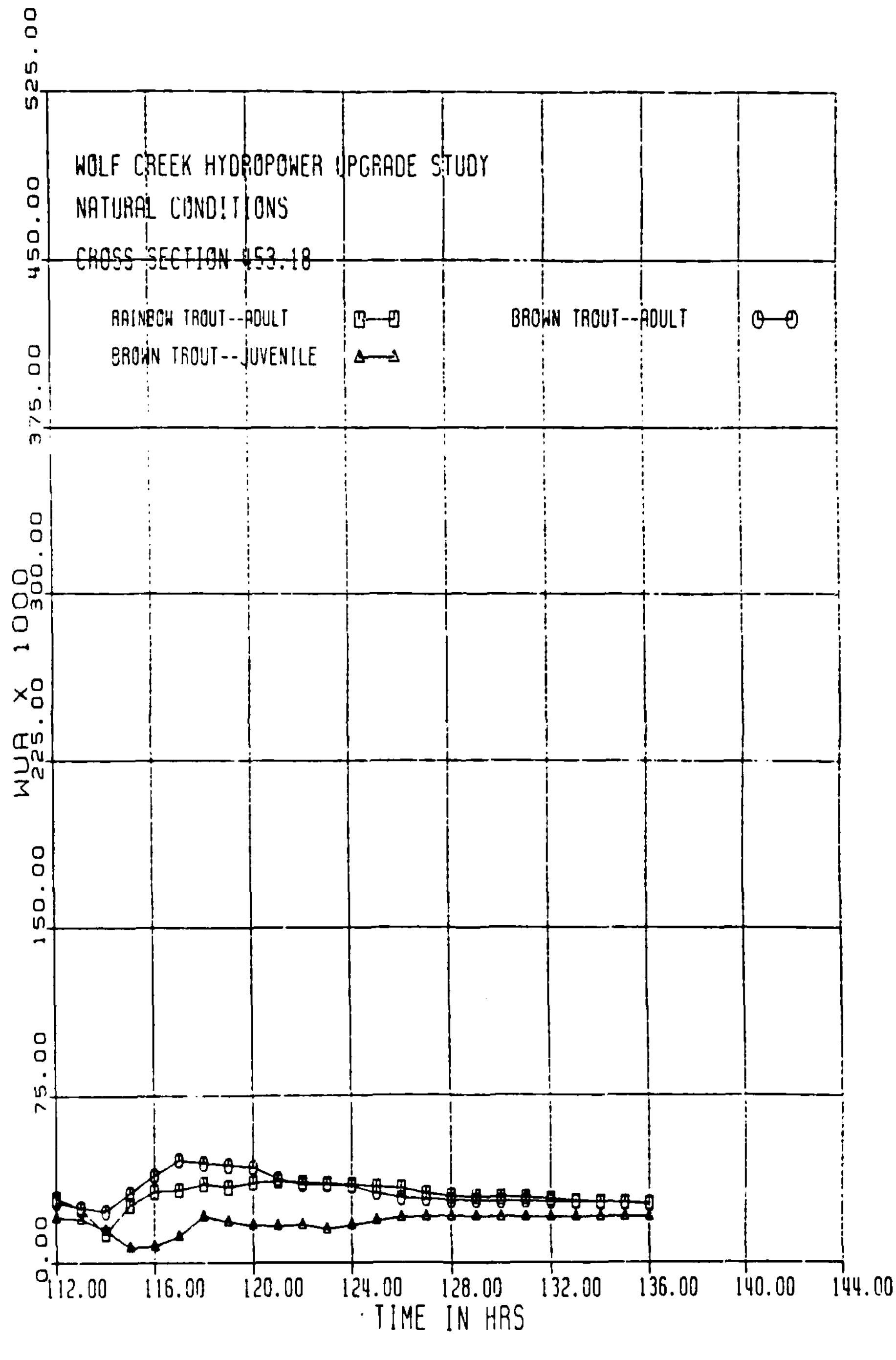
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

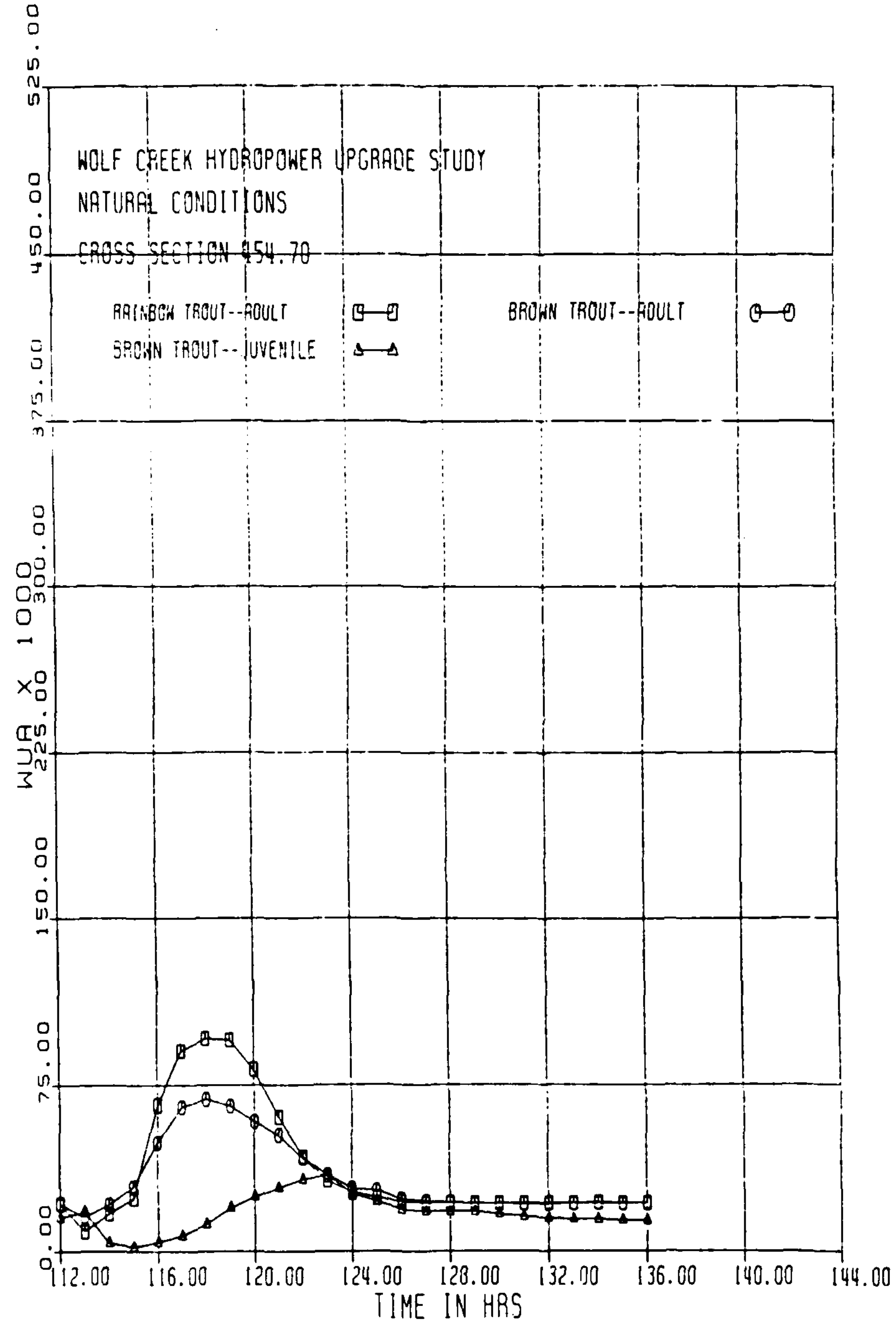

WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 451.20
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00
140.00
144.00
TIME IN HRS


WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 451.70
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00
140.00
144.00
TIME IN HRS

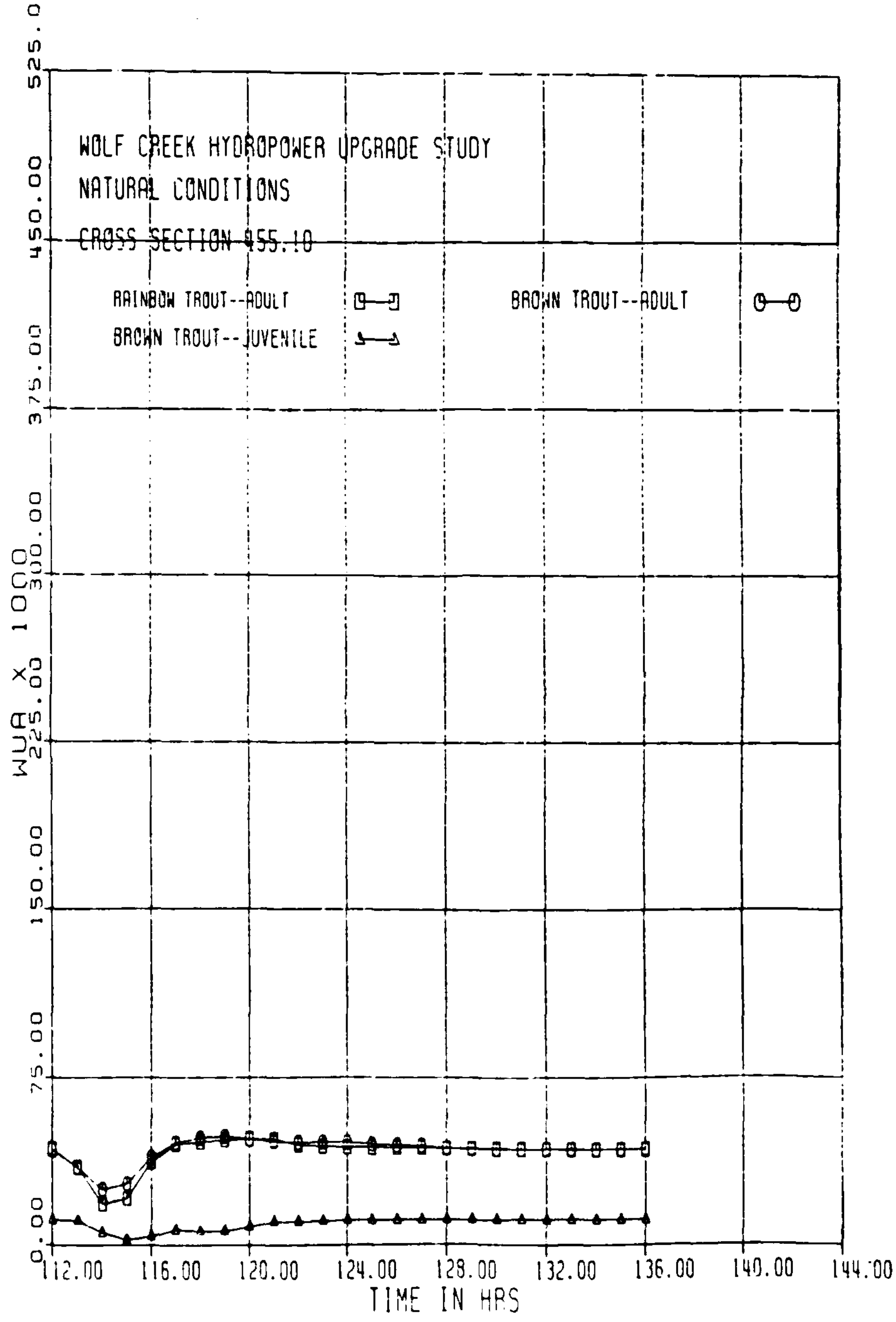


WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 452.76
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00
140.00
144.00
TIME IN HRS

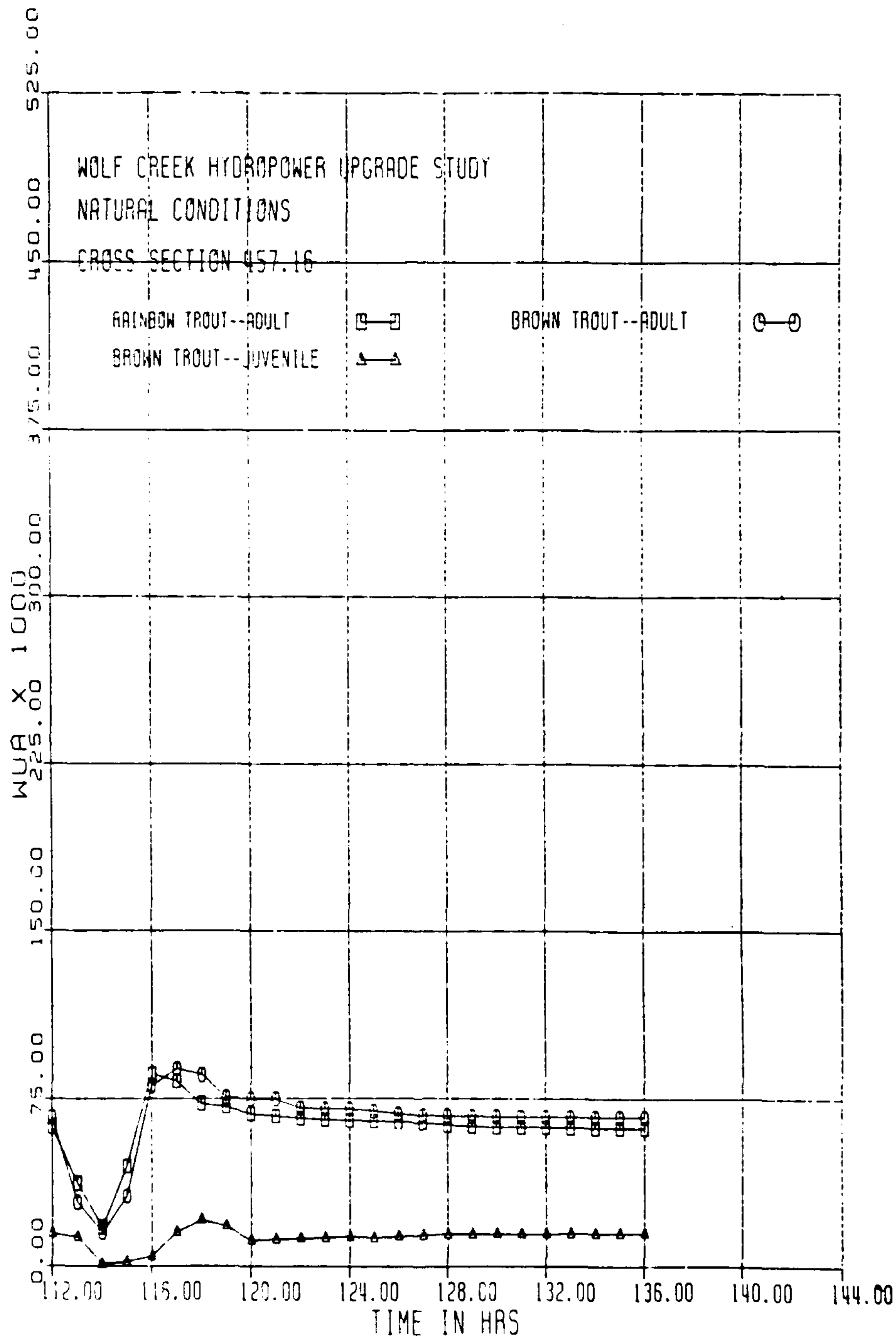

WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 453.18
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00
140.00
144.00
TIME IN HRS

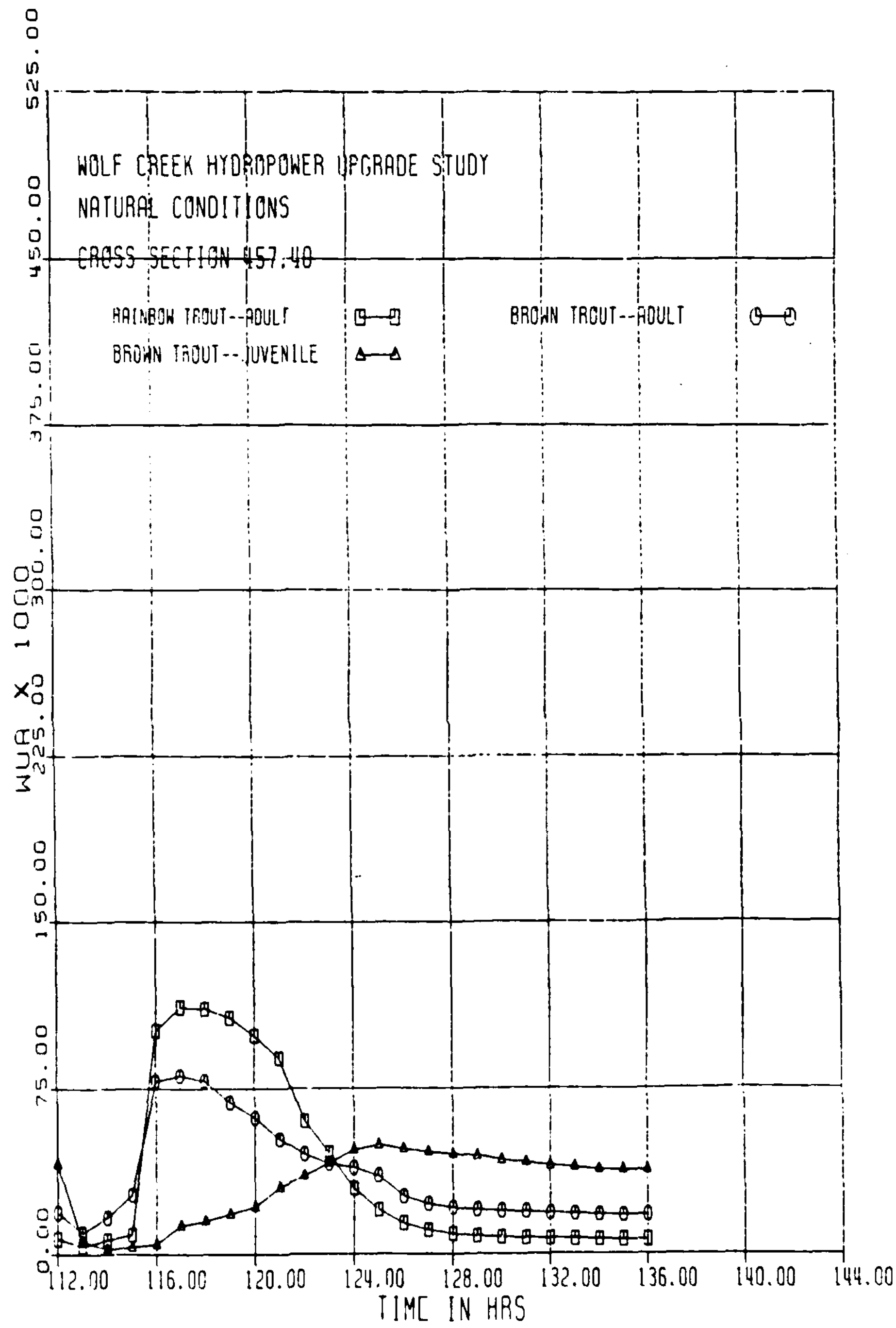


WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 454.70
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00
140.00
144.00
TIME IN HRS

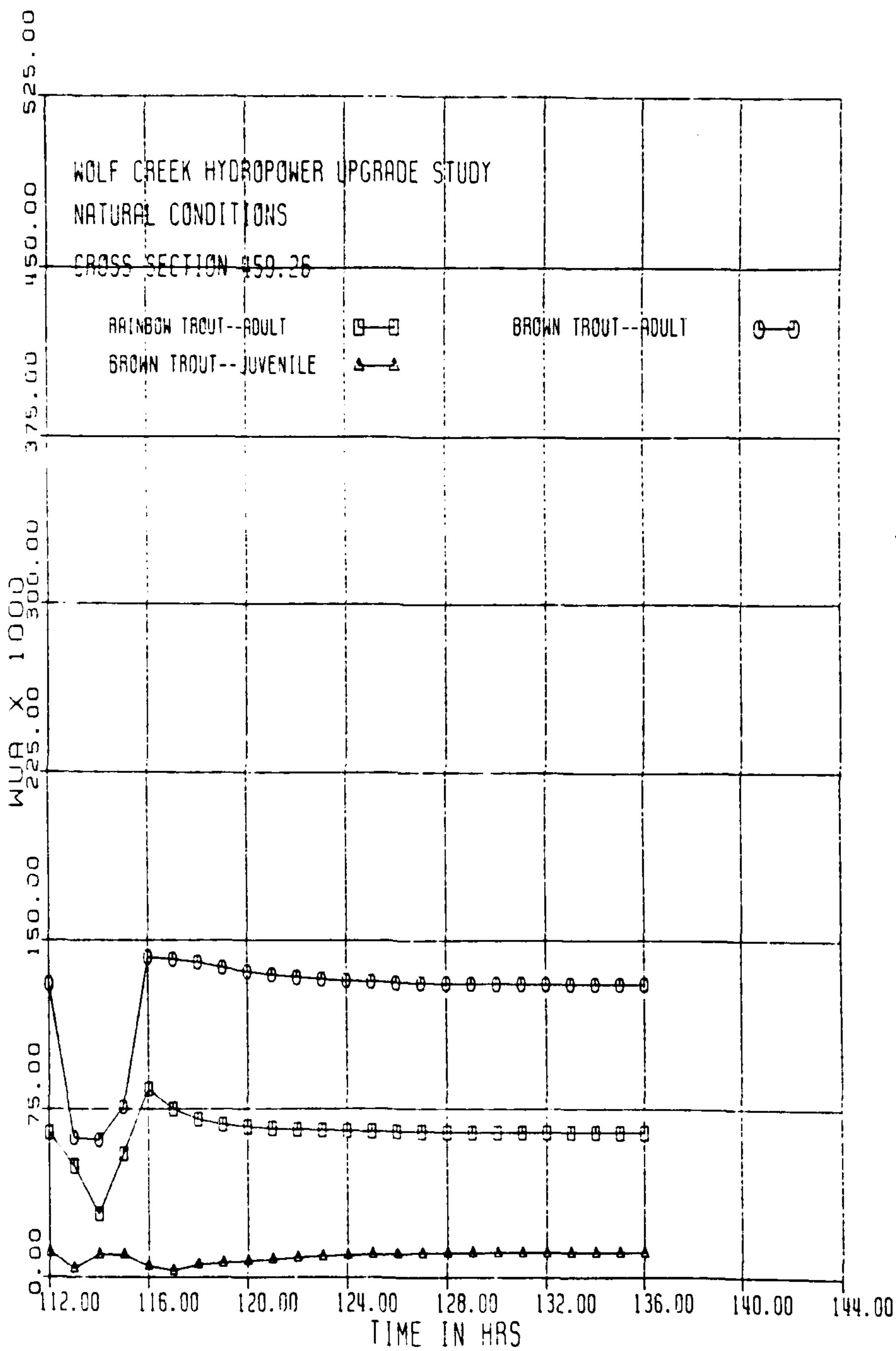


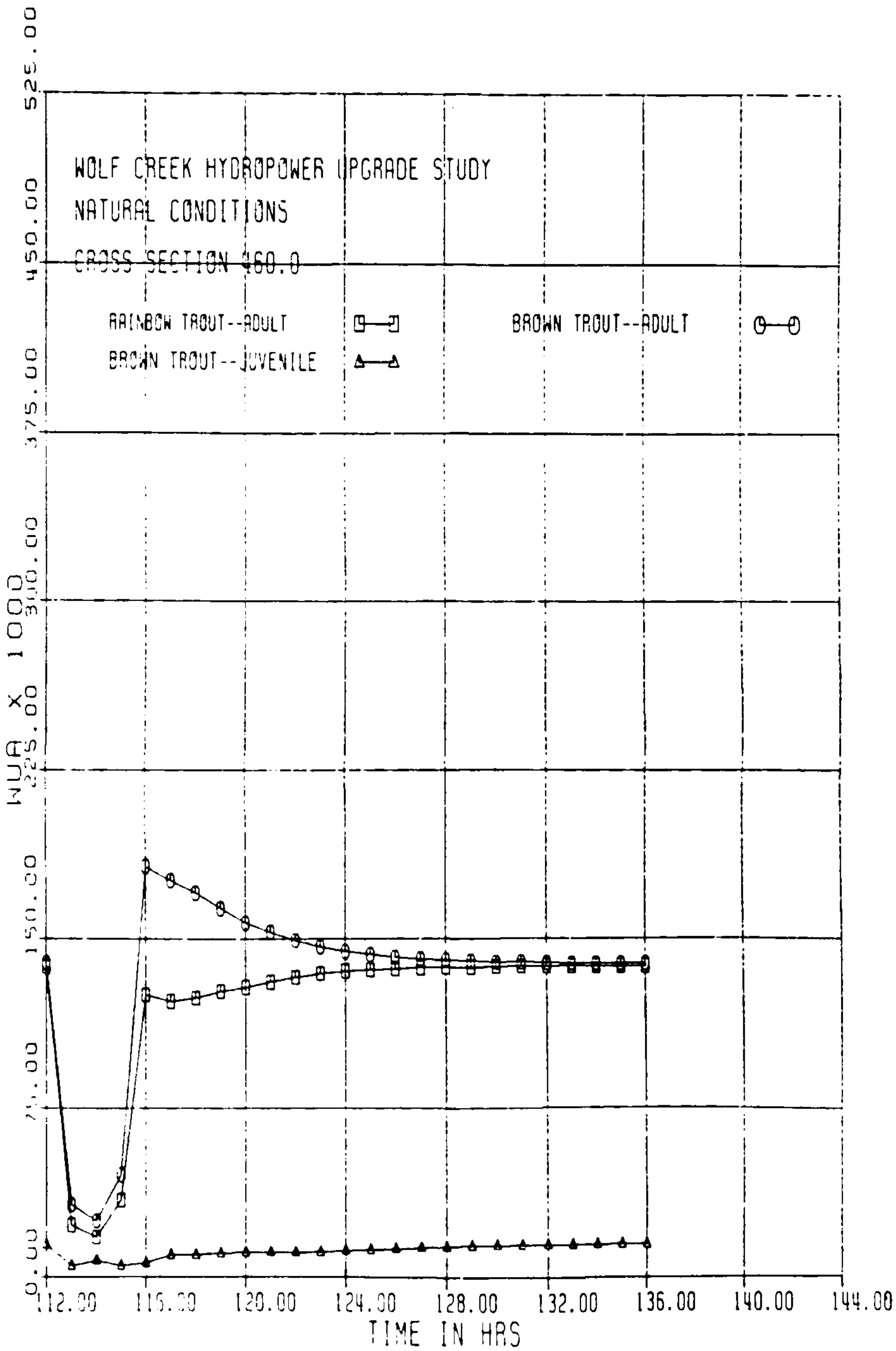
WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 455.10
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00
140.00
144.00
TIME IN HRS

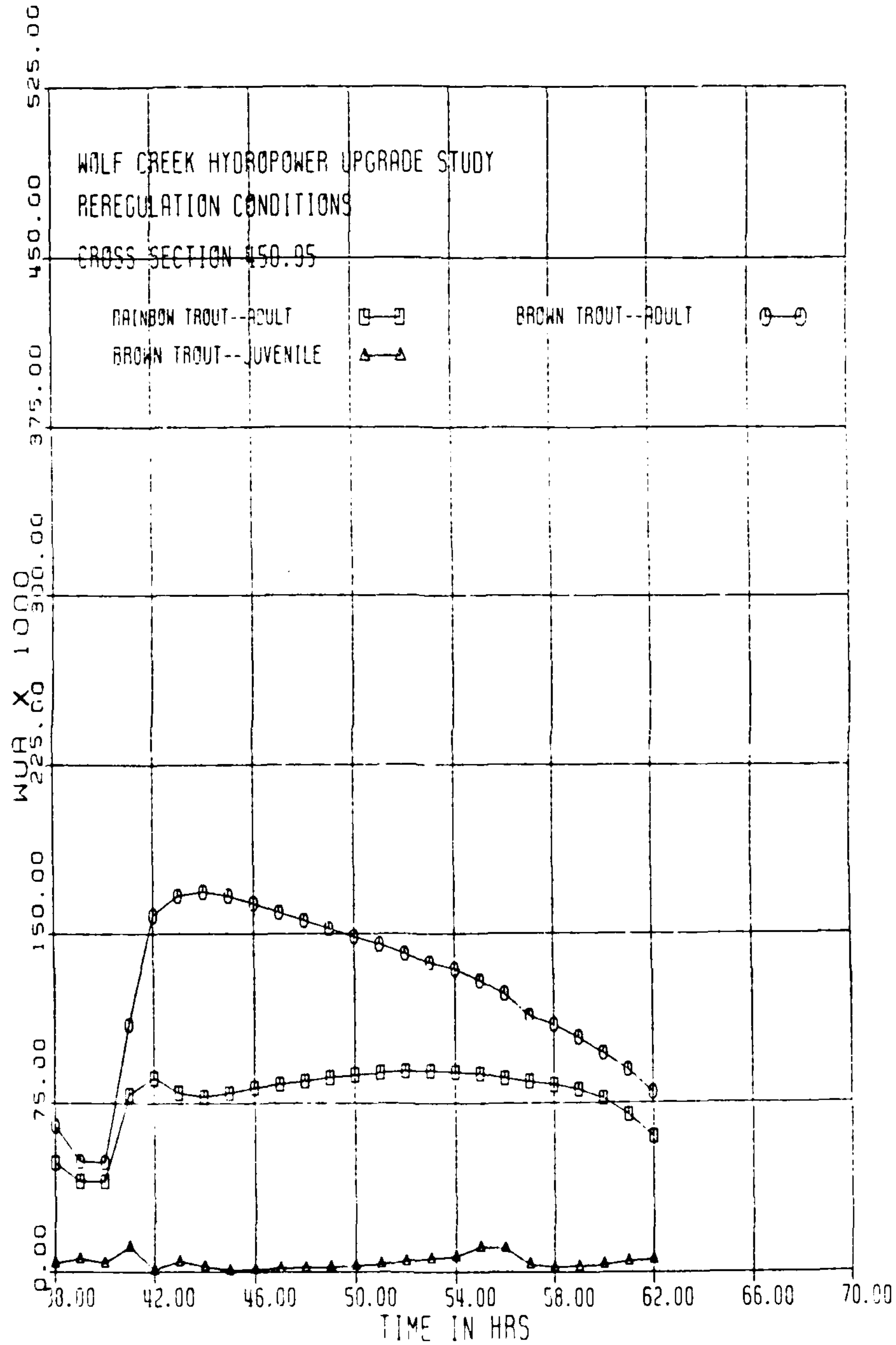

WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 457.16
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00
140.00
144.00
TIME IN HRS

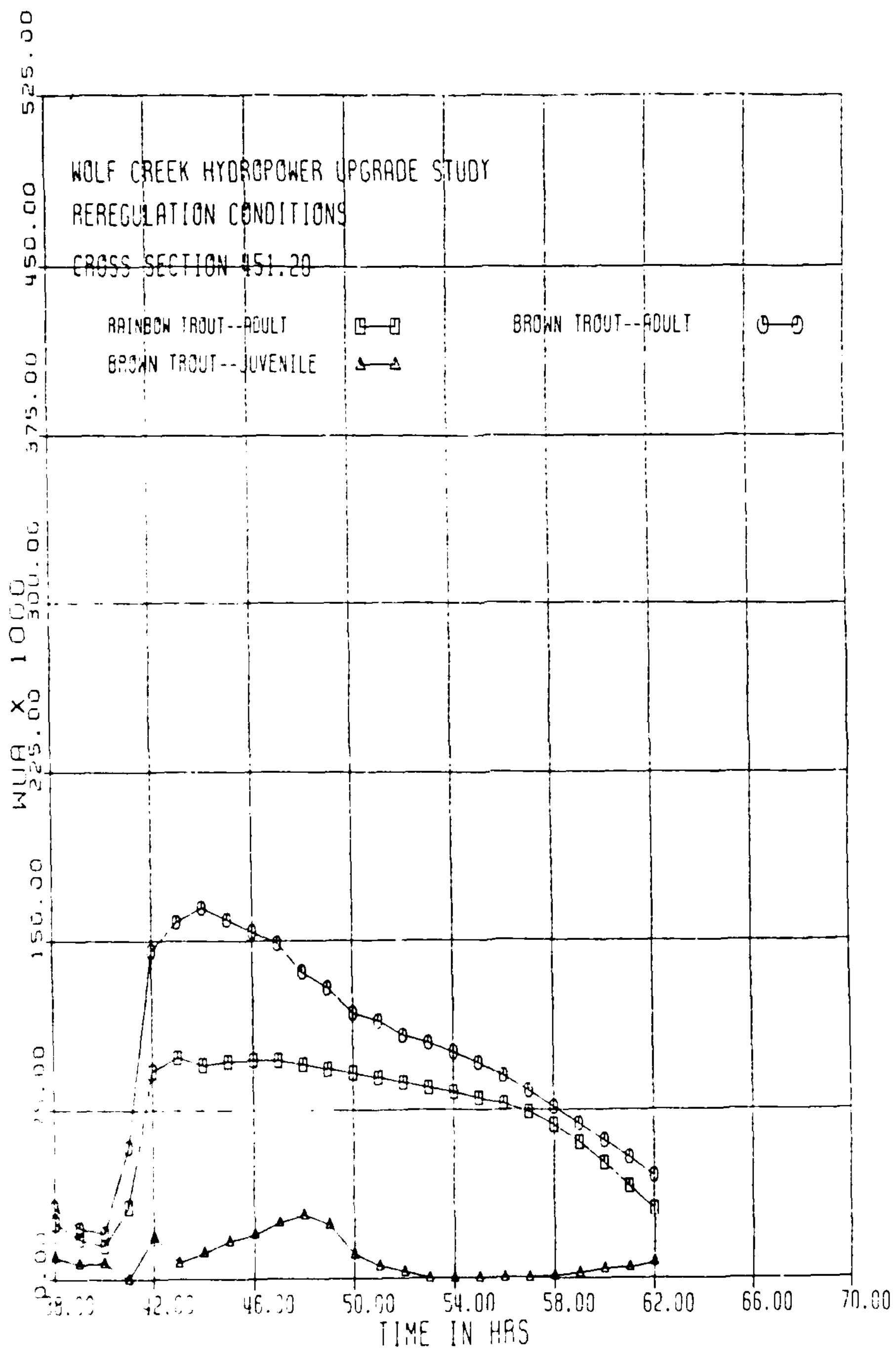


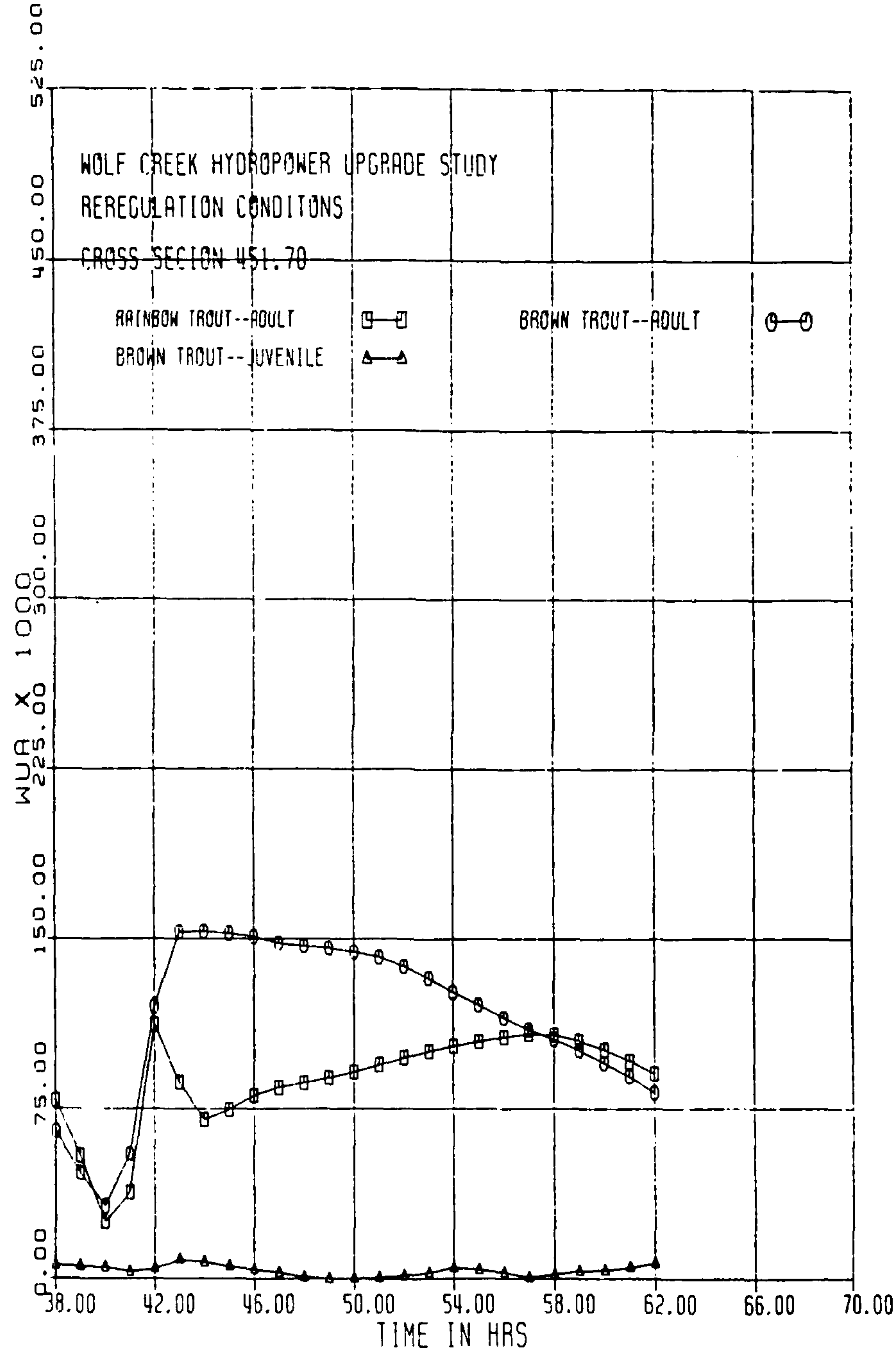
WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 457.40
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00
140.00
144.00
TIME IN HRS

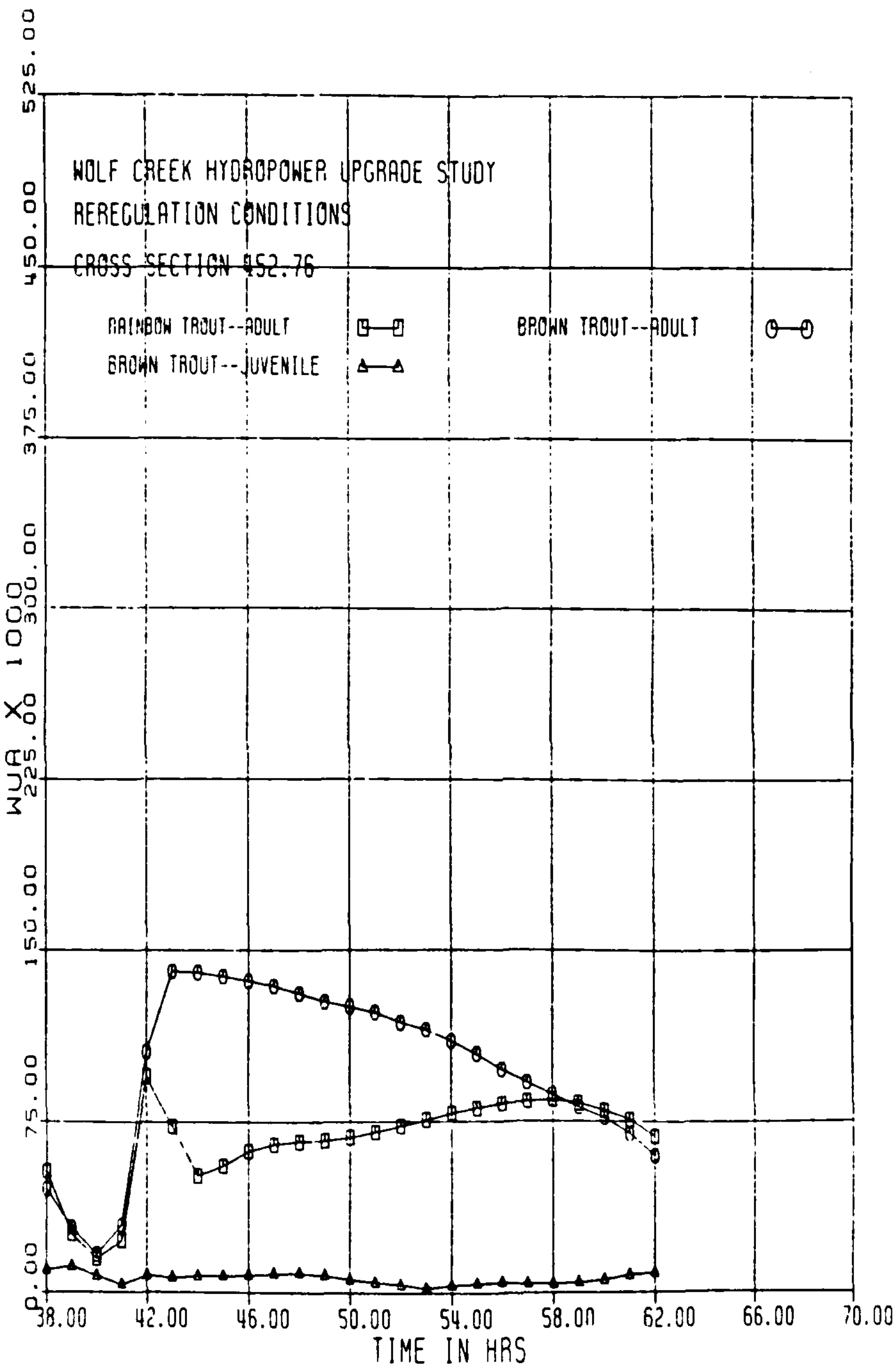

WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 459.26
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00
140.00
144.00
TIME IN HRS


WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 460.0
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
TIME IN HRS
0.00
150.00
225.00
300.00
375.00
450.00
525.00
112.00
120.00
124.00
128.00
132.00
136.00
140.00
144.00

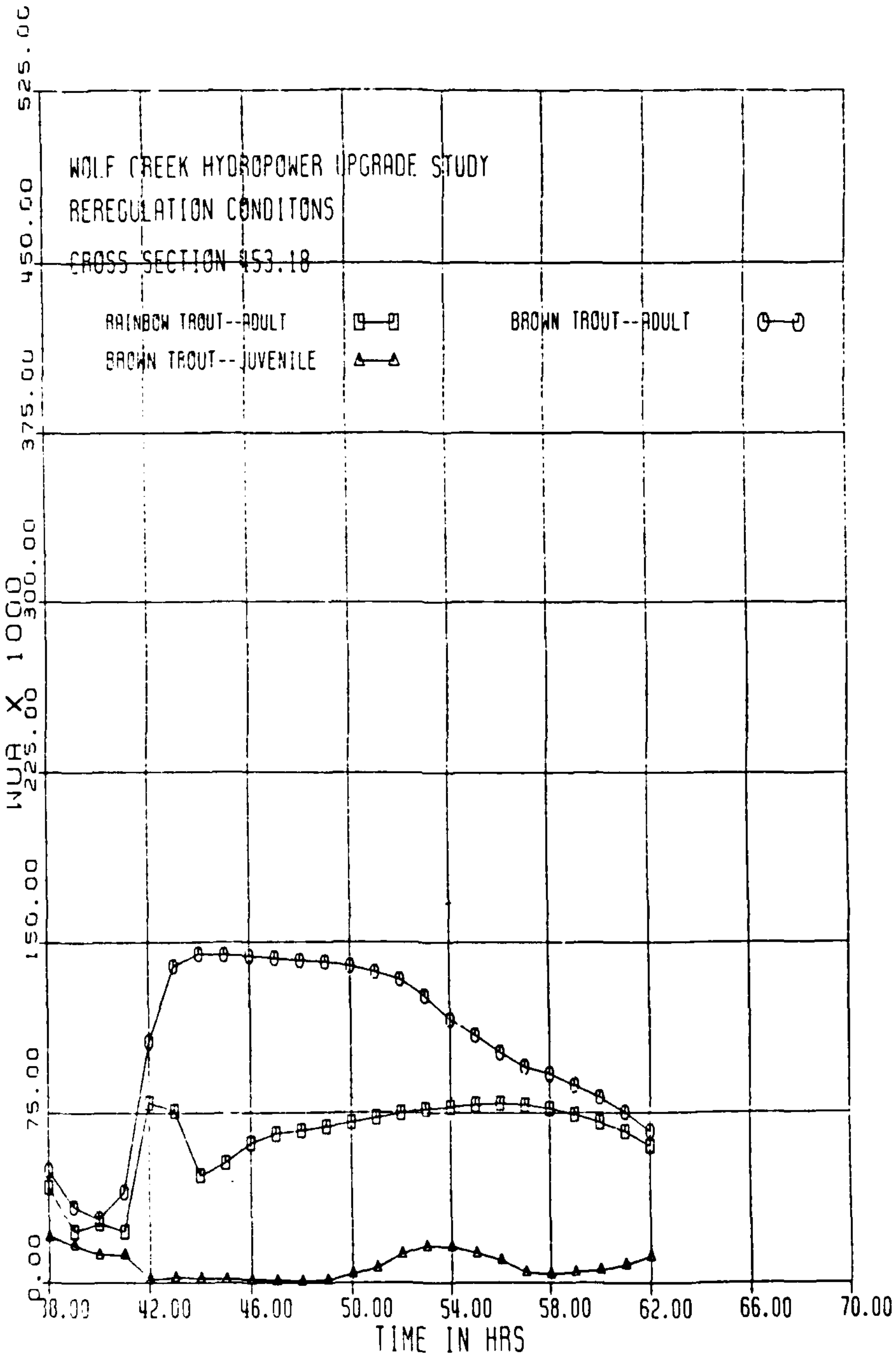

WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 450.95
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
TIME IN HRS
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
42.00
46.00
50.00
54.00
58.00
62.00
66.00
70.00

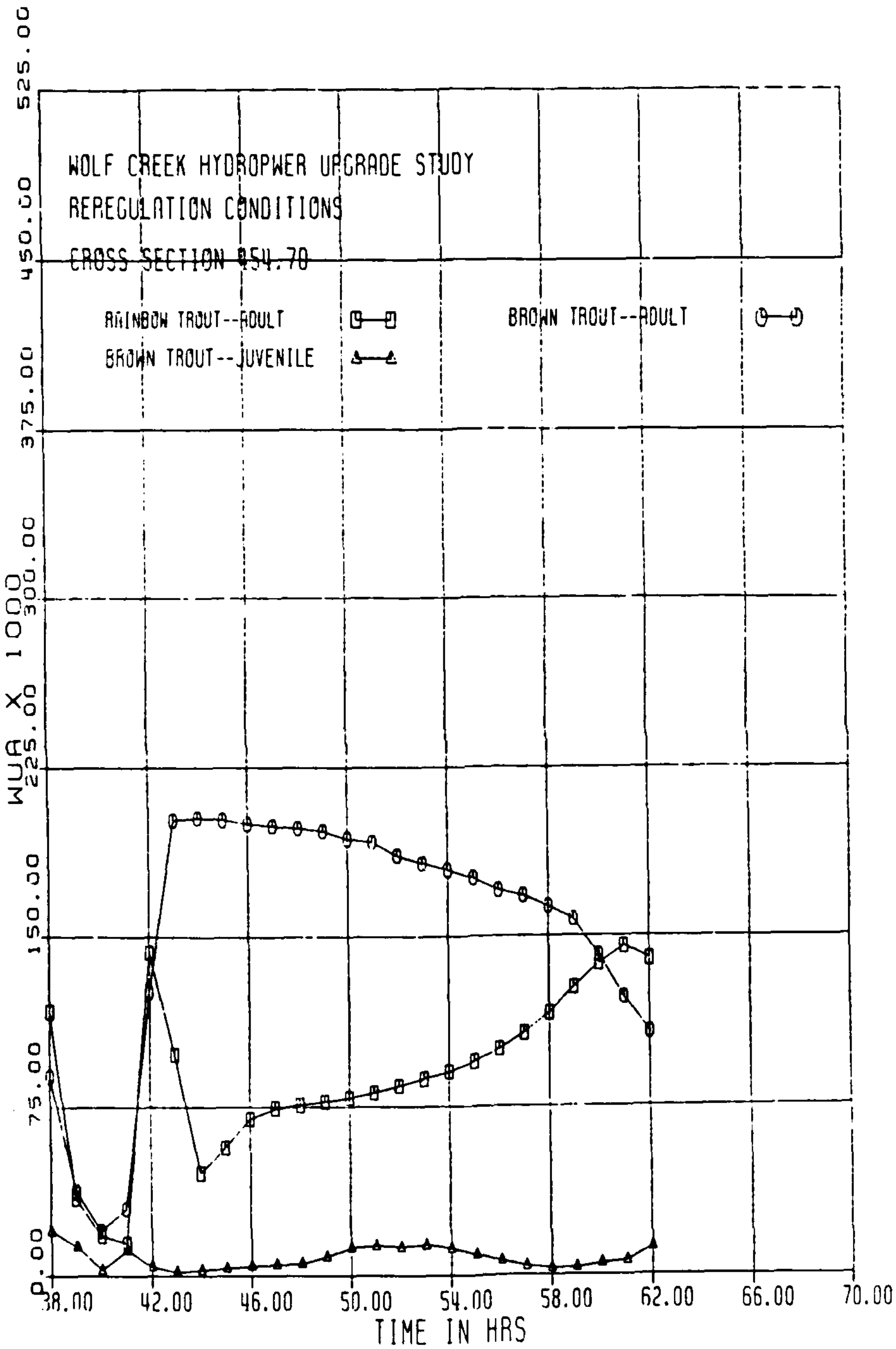

WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 451.20
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
525.00
450.00
375.00
300.00
225.00
150.00
42.00
46.00
50.00
54.00
58.00
62.00
66.00
70.00
TIME IN HRS

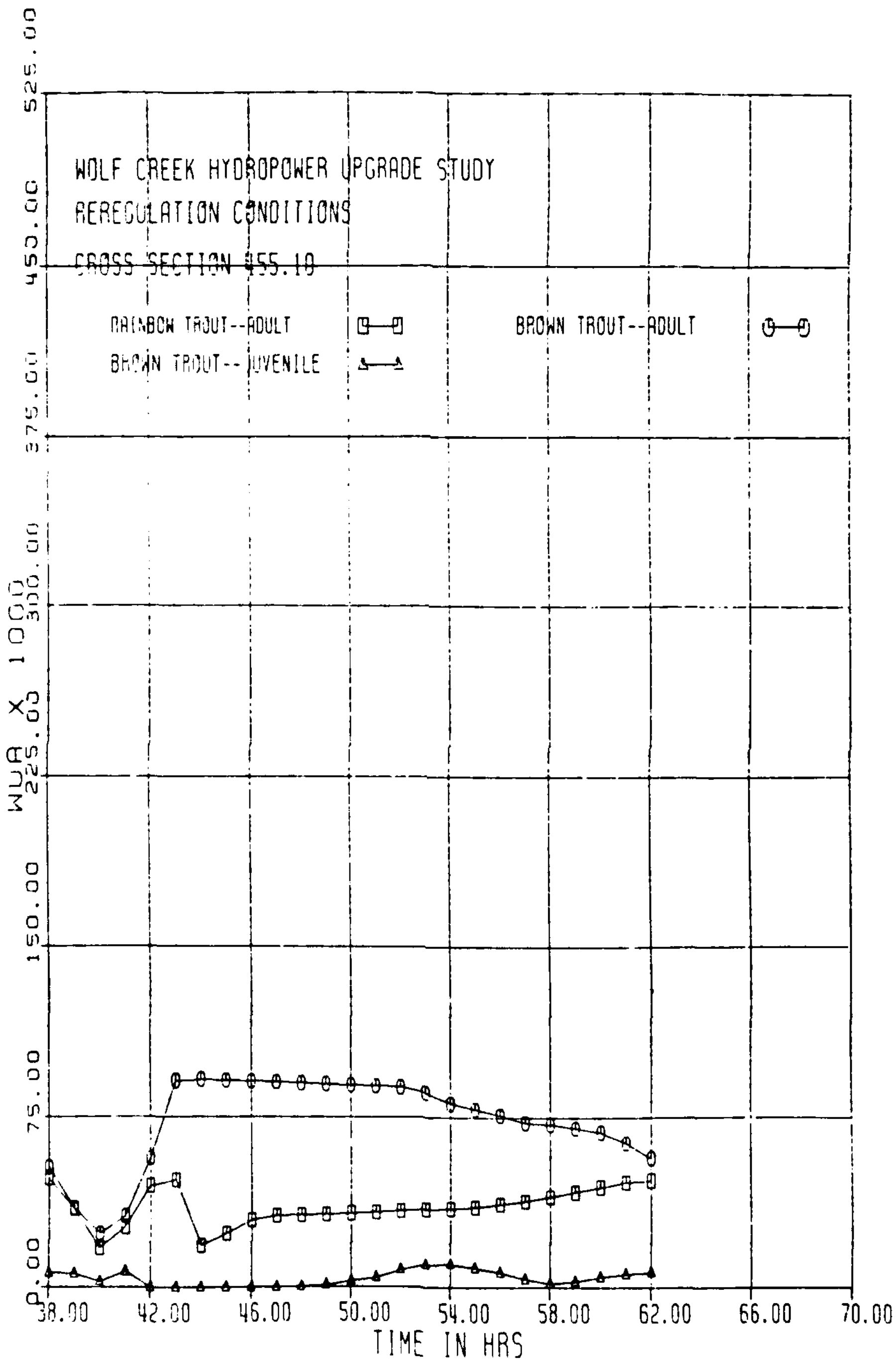

WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITONS
CROSS SECION 451.70
RAINBOW TROUT--ADULT
BROWN TROUT--JUVENILE
BROWN TROUT--ADULT
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
38.00
42.00
46.00
50.00
54.00
58.00
62.00
66.00
70.00
TIME IN HRS

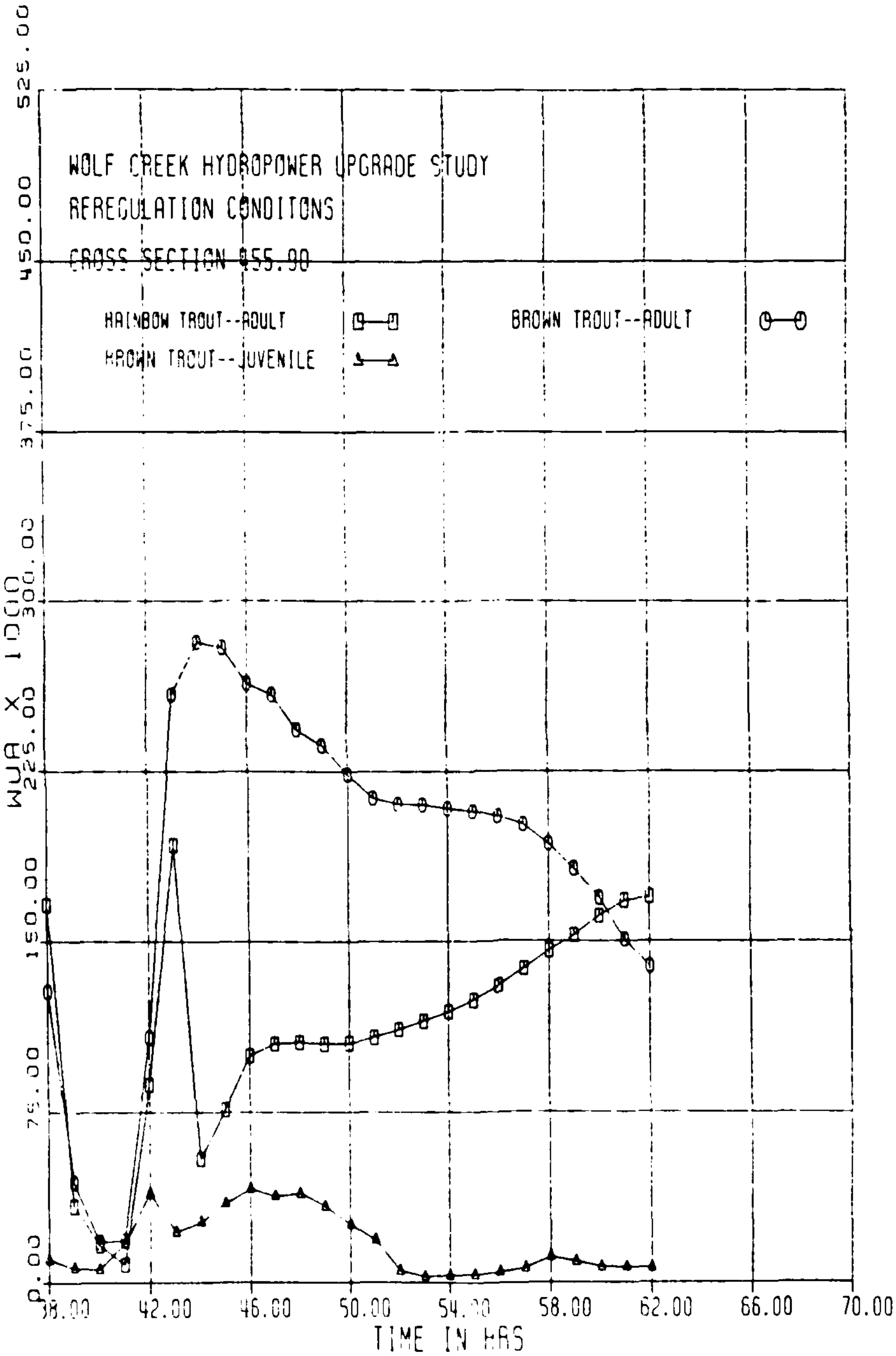


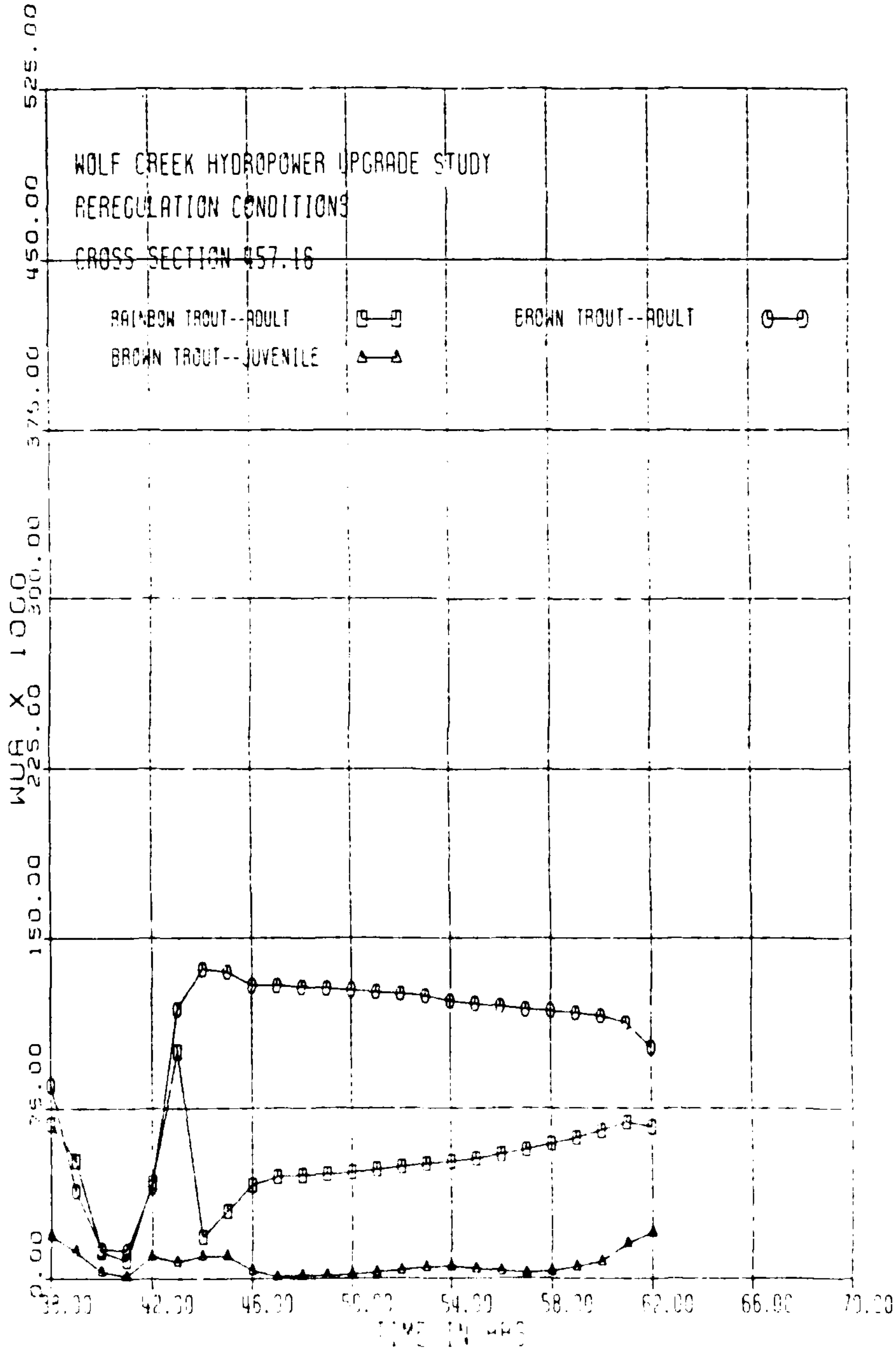
WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 452.76
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
38.00
42.00
46.00
50.00
54.00
58.00
62.00
66.00
70.00
TIME IN HRS


WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITONS
CROSS SECTION 453.18
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
38.00
42.00
46.00
50.00
54.00
58.00
62.00
66.00
70.00
TIME IN HRS

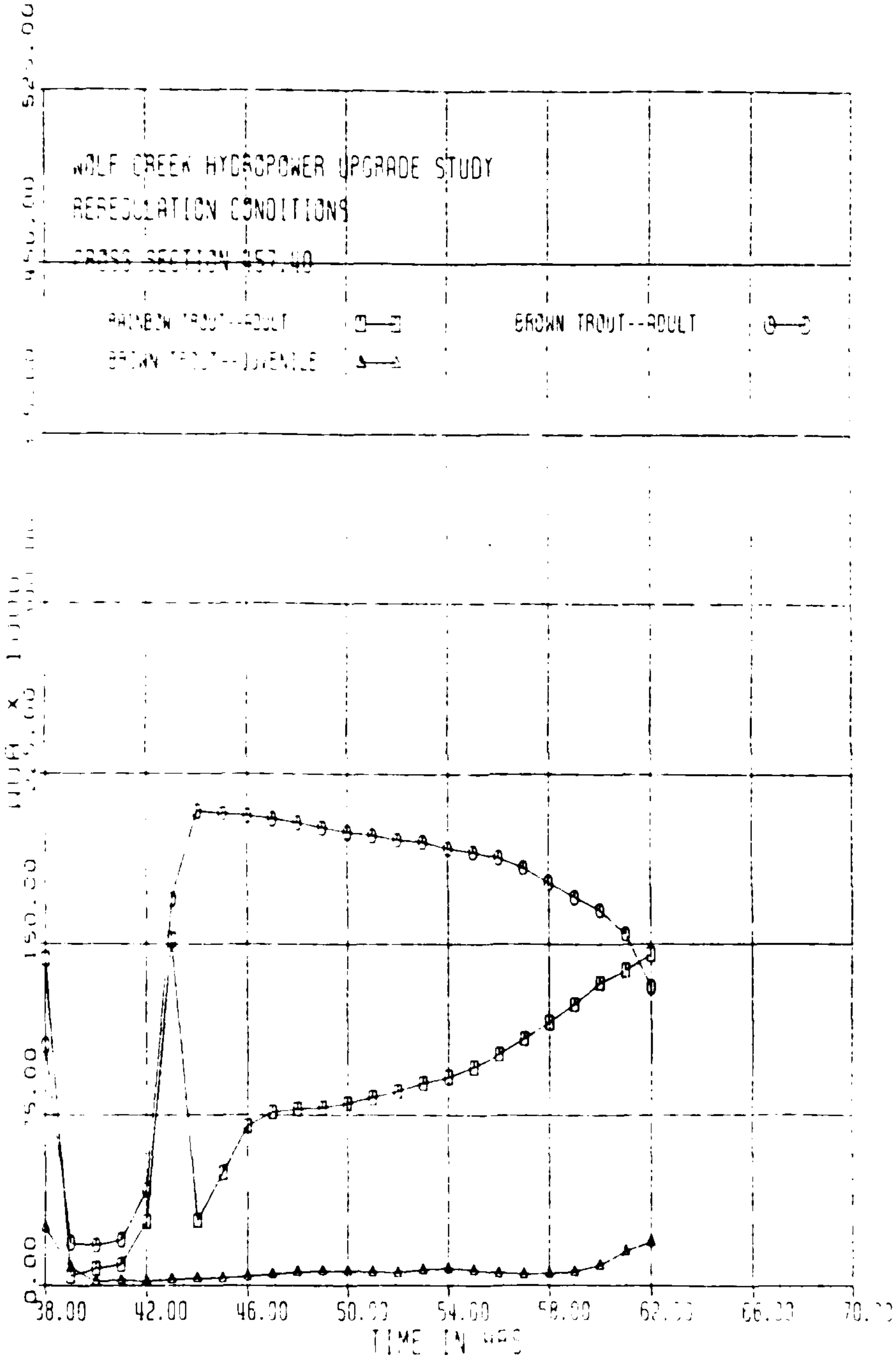

WOLF CREEK HYDROPWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 454.70
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
525.00
450.00
375.00
300.00
225.00
150.00
75.00
0.00
38.00
42.00
46.00
50.00
54.00
58.00
62.00
66.00
70.00
TIME IN HRS


WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 455.10
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
38.00
42.00
46.00
50.00
54.00
58.00
62.00
66.00
70.00
TIME IN HRS

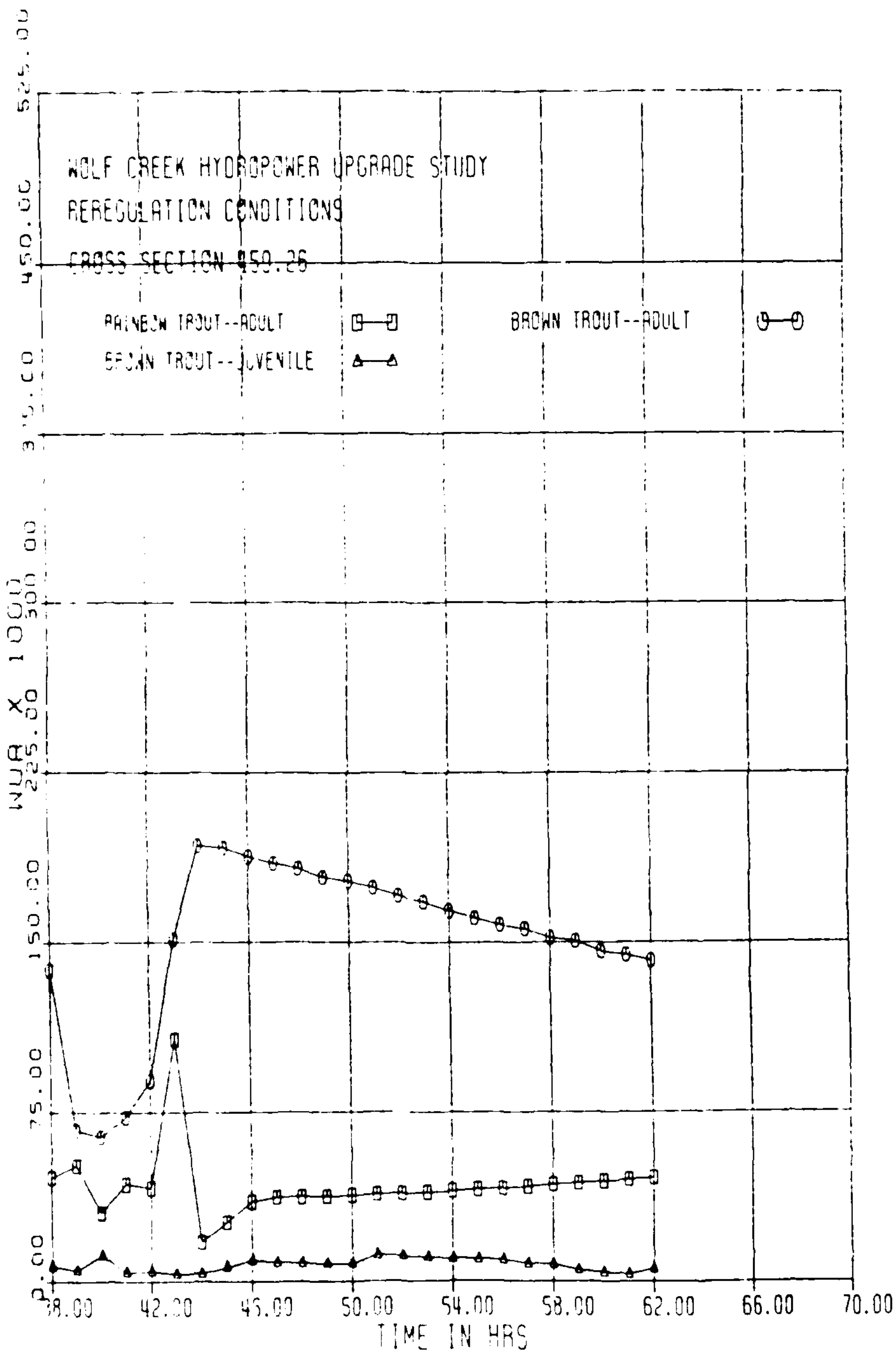

WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITONS
CROSS SECTION 455.90
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
38.00
42.00
46.00
50.00
54.00
58.00
62.00
66.00
70.00
TIME IN HRS



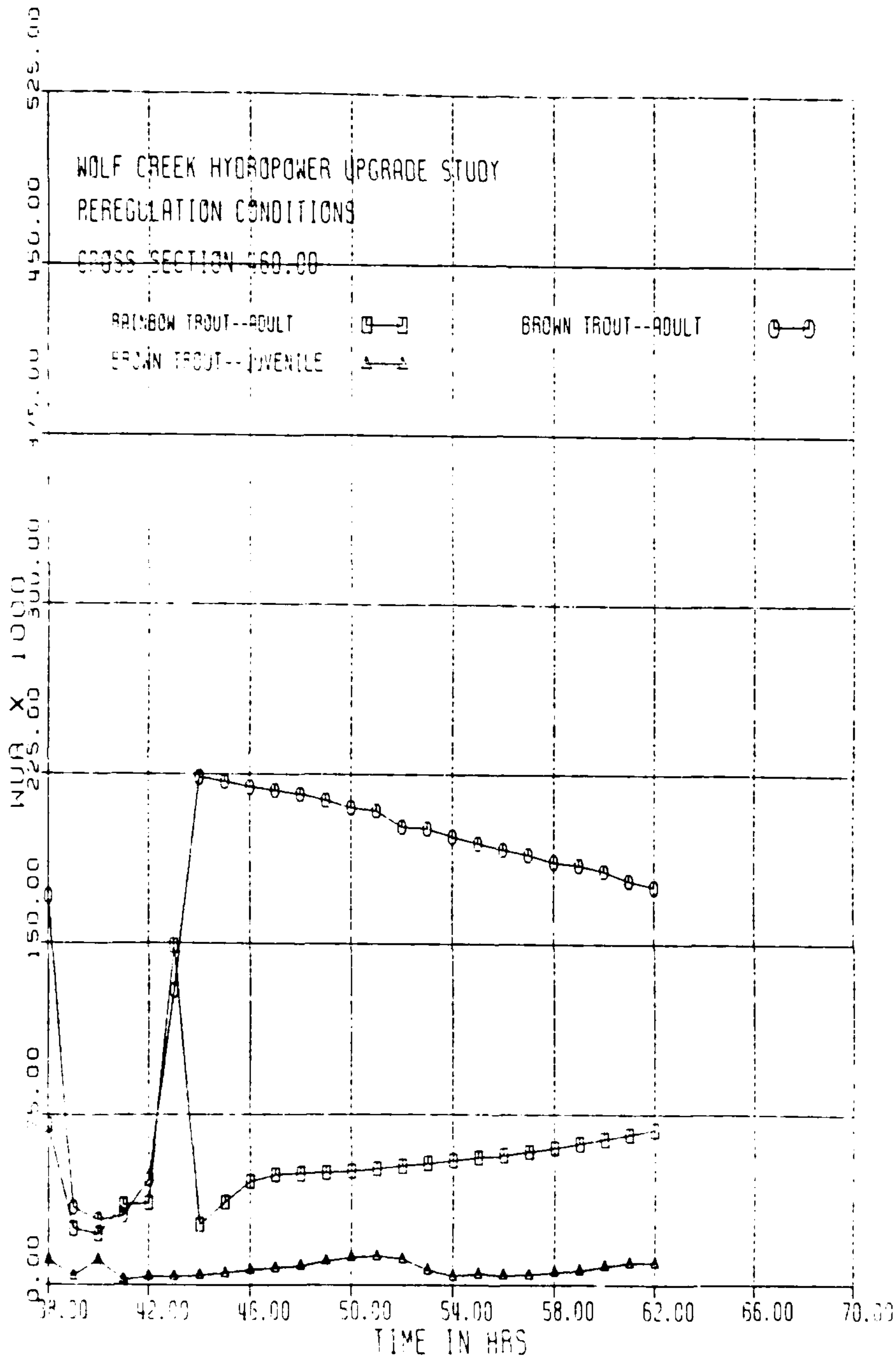
WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 457.16
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
TIME IN HRS



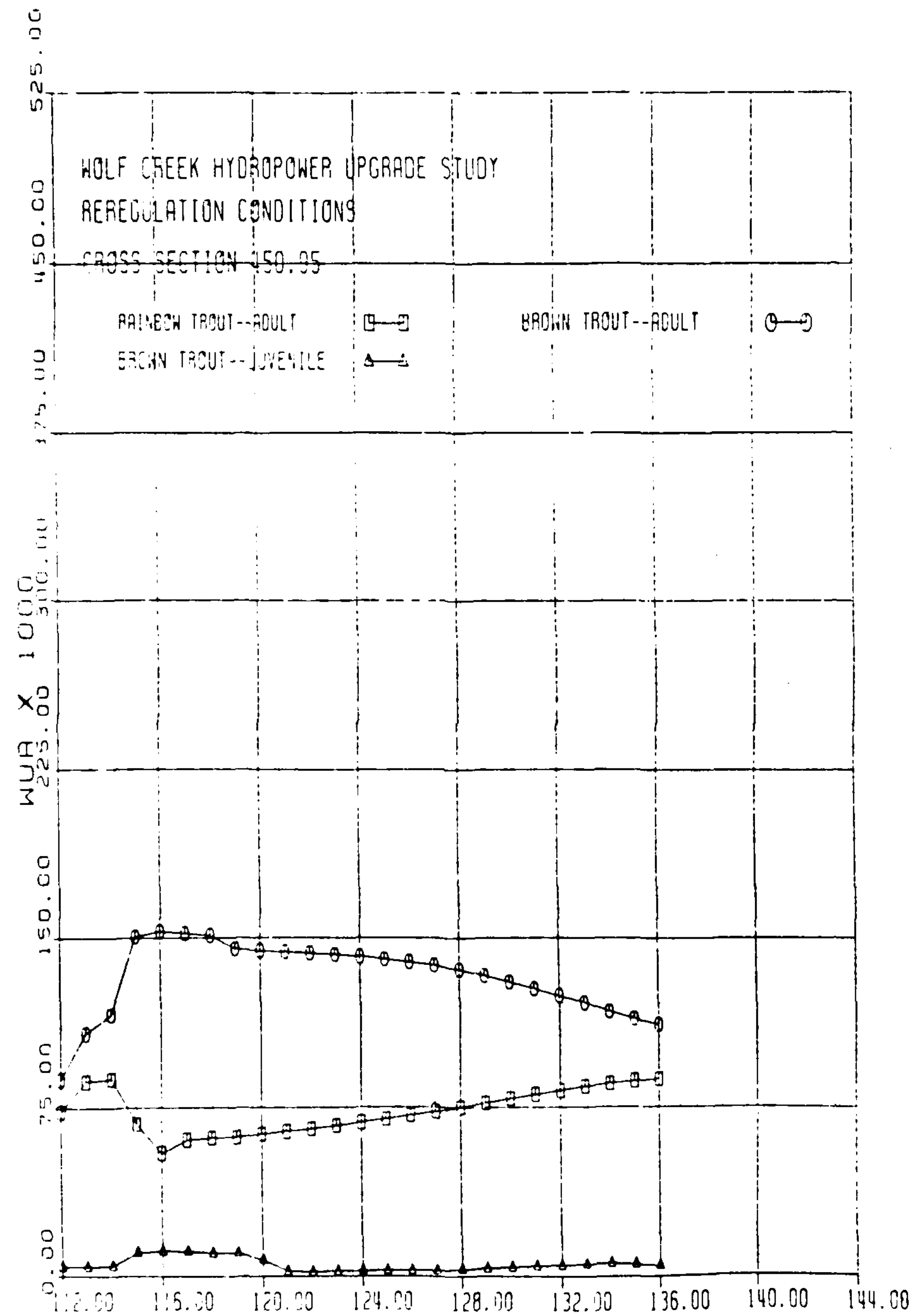
WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 357.40
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
TIME IN HRS



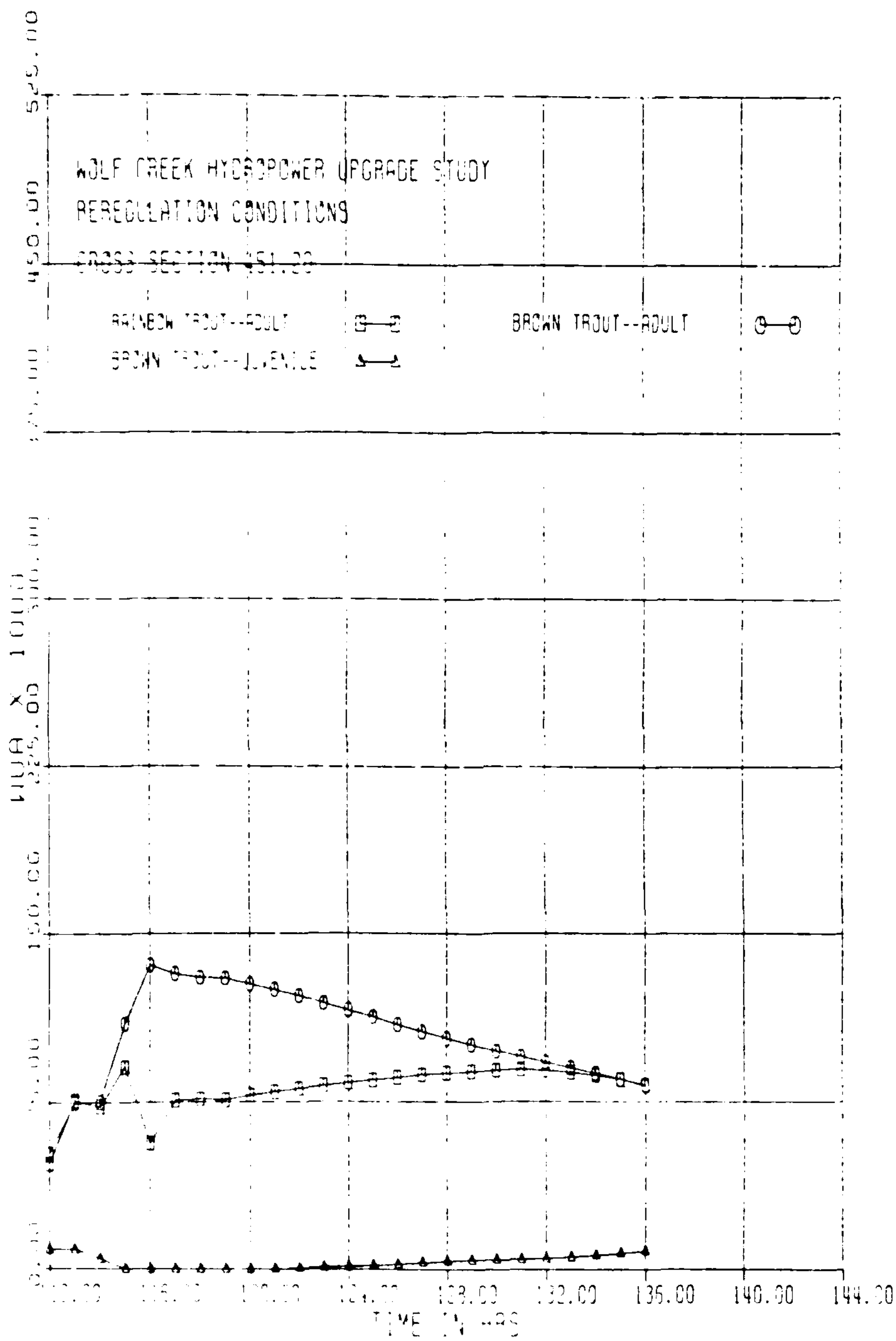
WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 459.26
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
TIME IN HRS

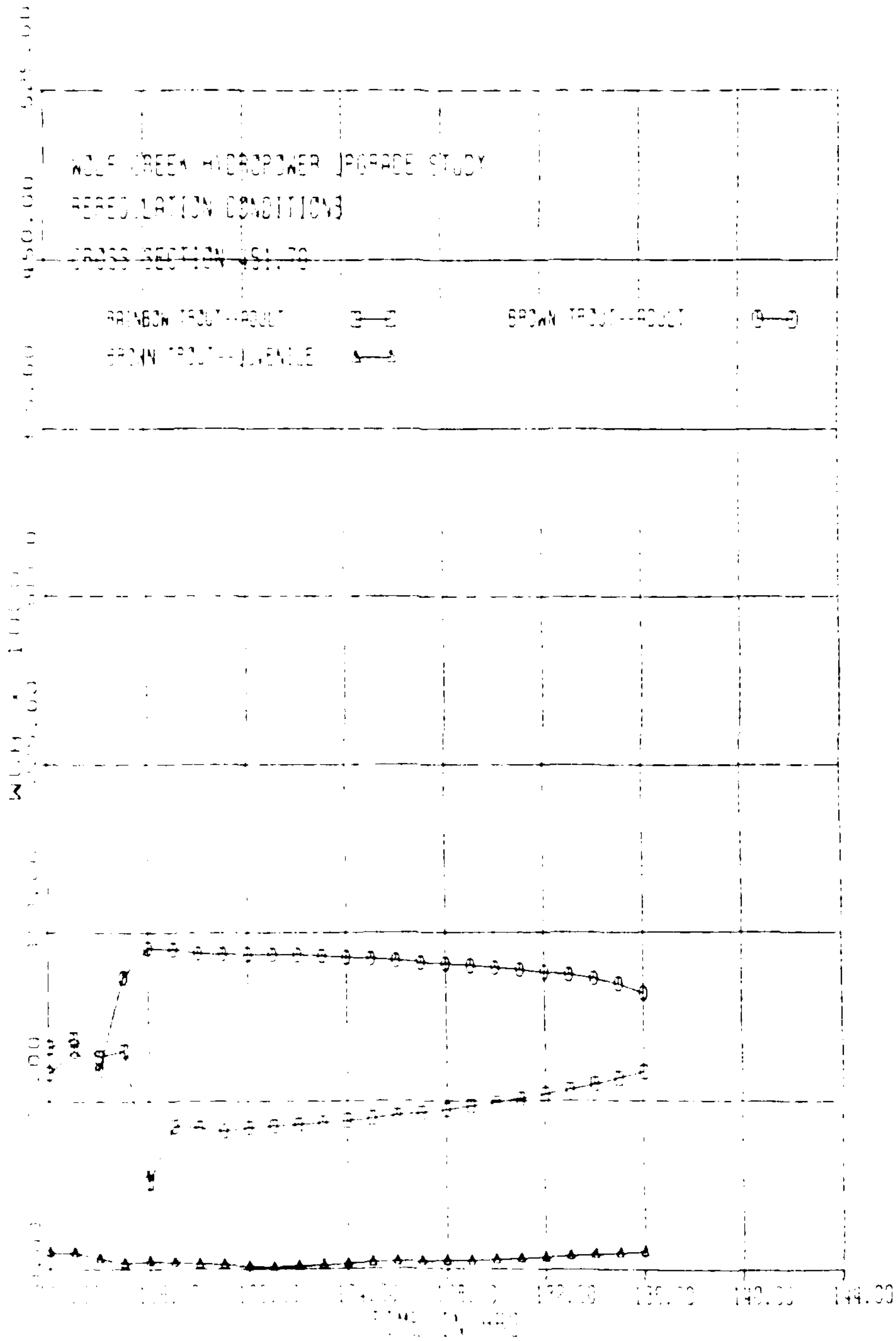


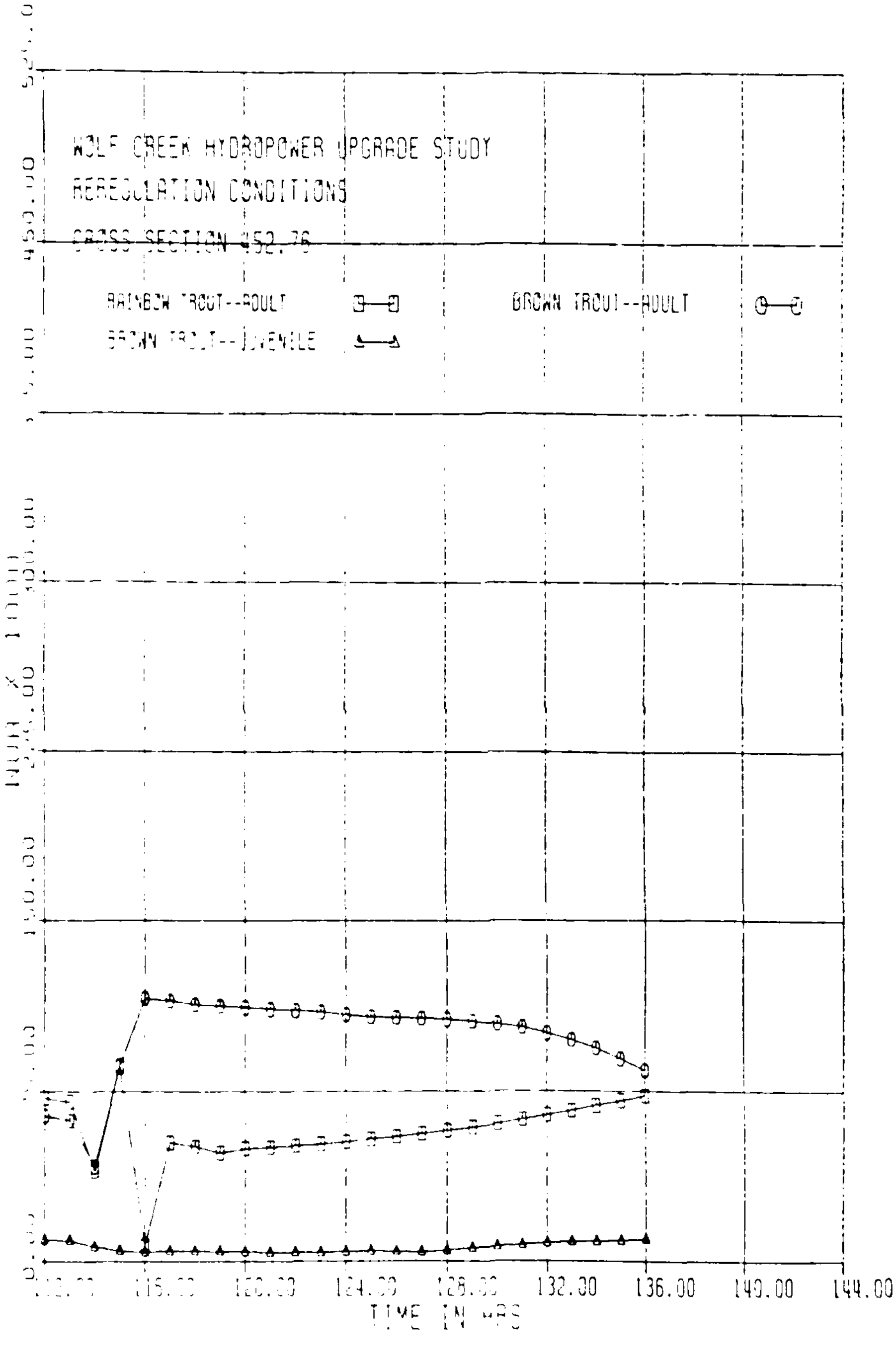
WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
TIME IN HRS

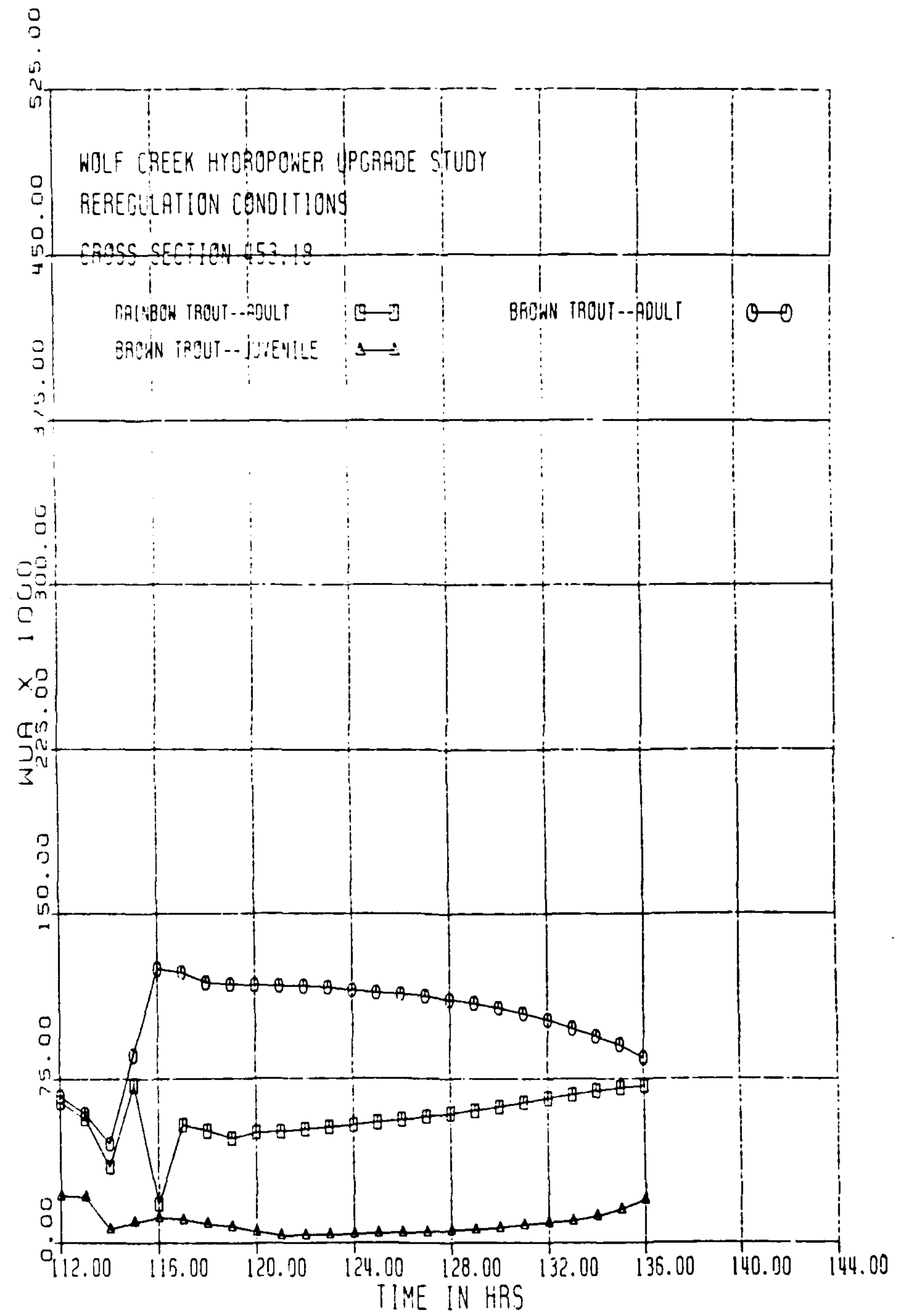


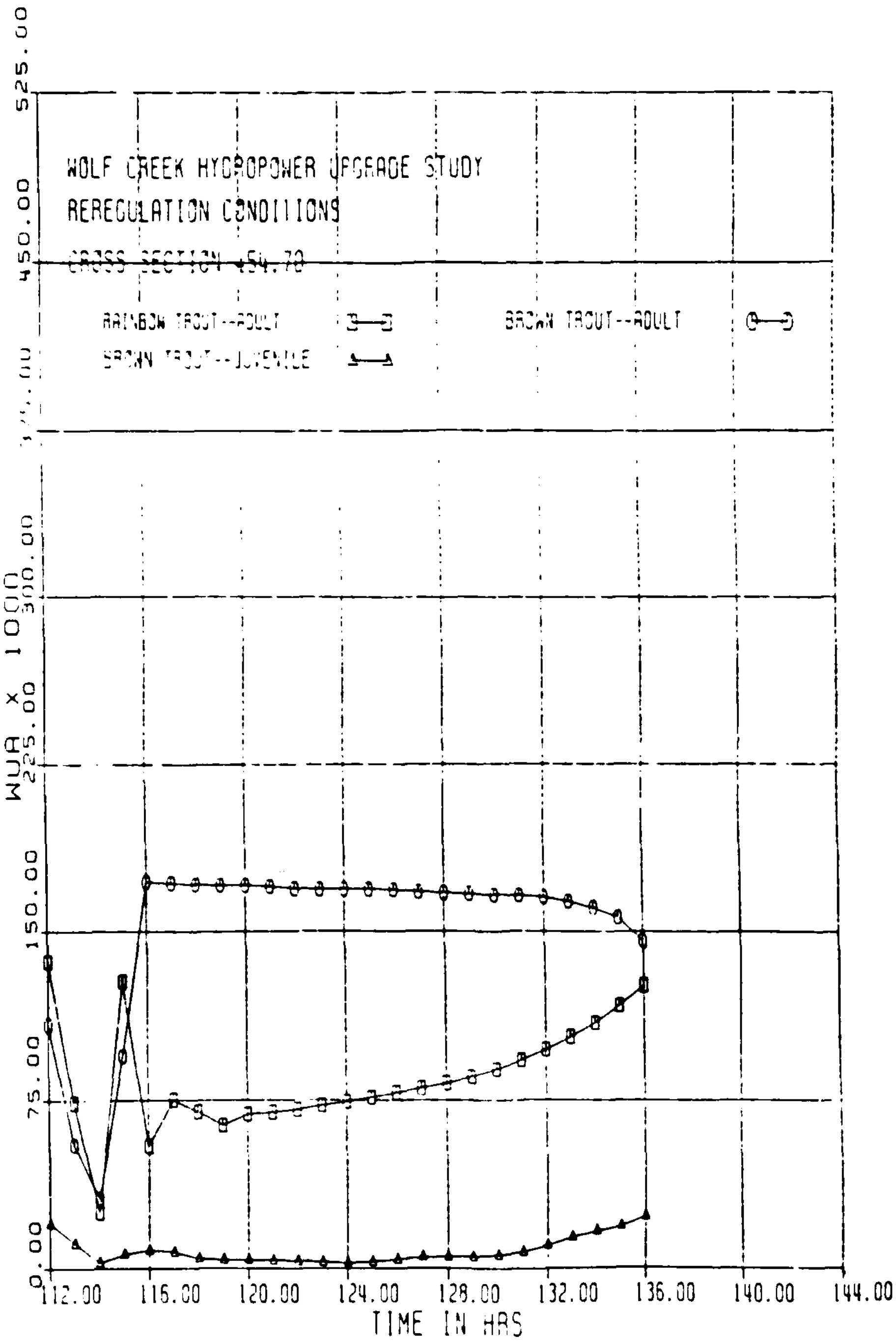
WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 450.95
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
TIME IN HRS


WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
BROWN TROUT--ADULT
TIME IN HRS
136.00
140.00
144.00
132.00

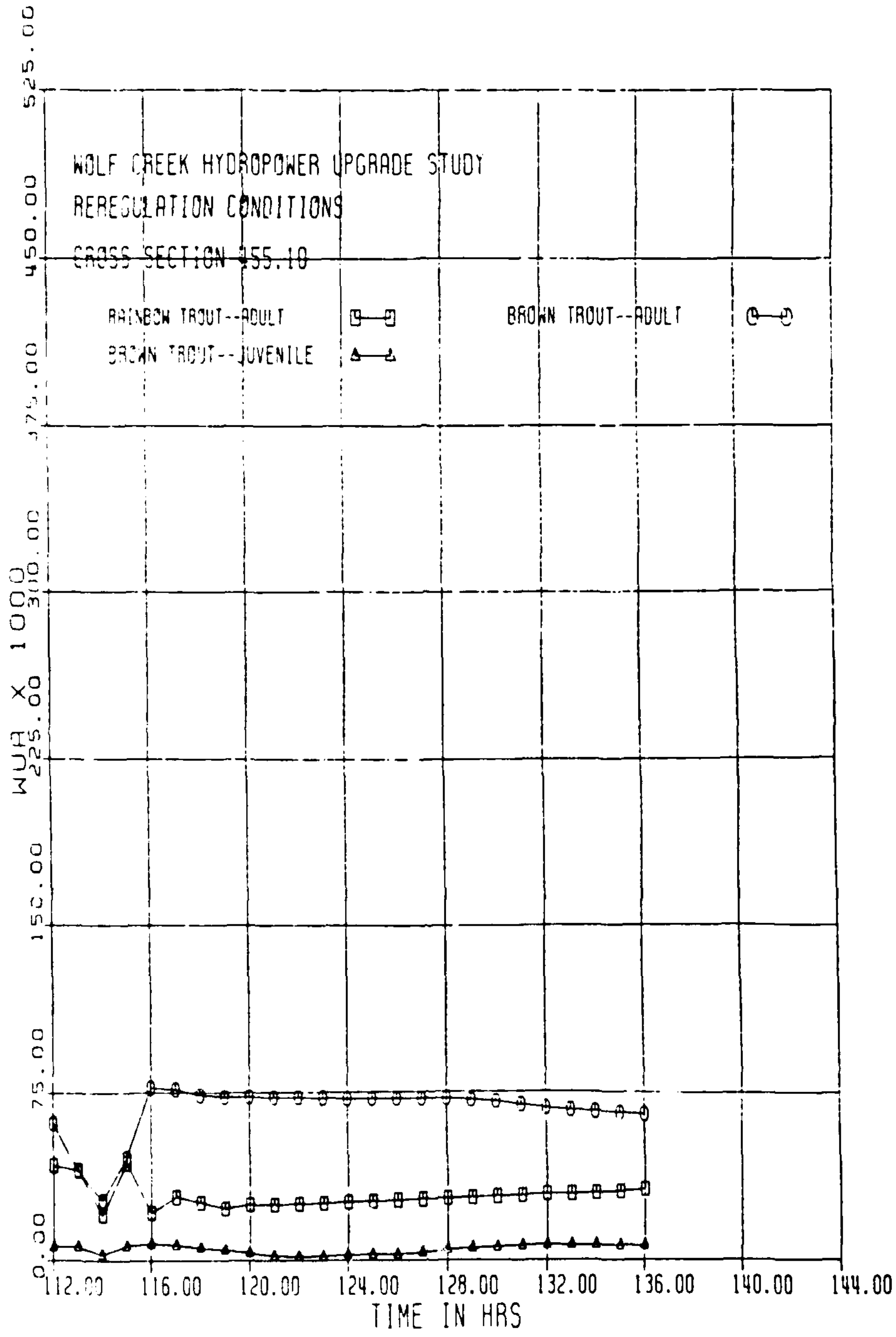

WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
140.00
144.00

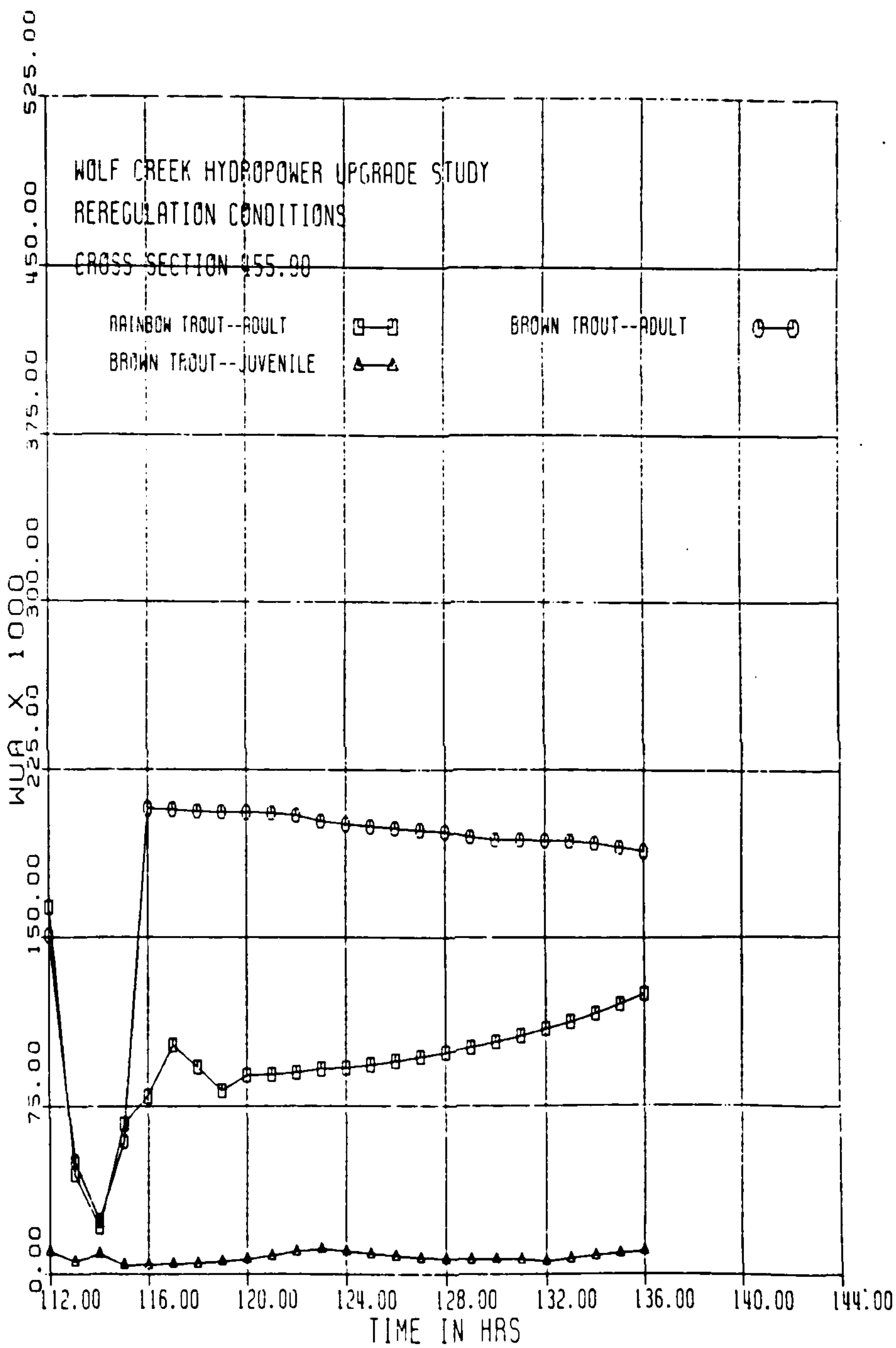

WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 452.76
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
132.00
136.00
140.00
144.00
TIME IN HRS


WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 453.18
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00
140.00
144.00
TIME IN HRS

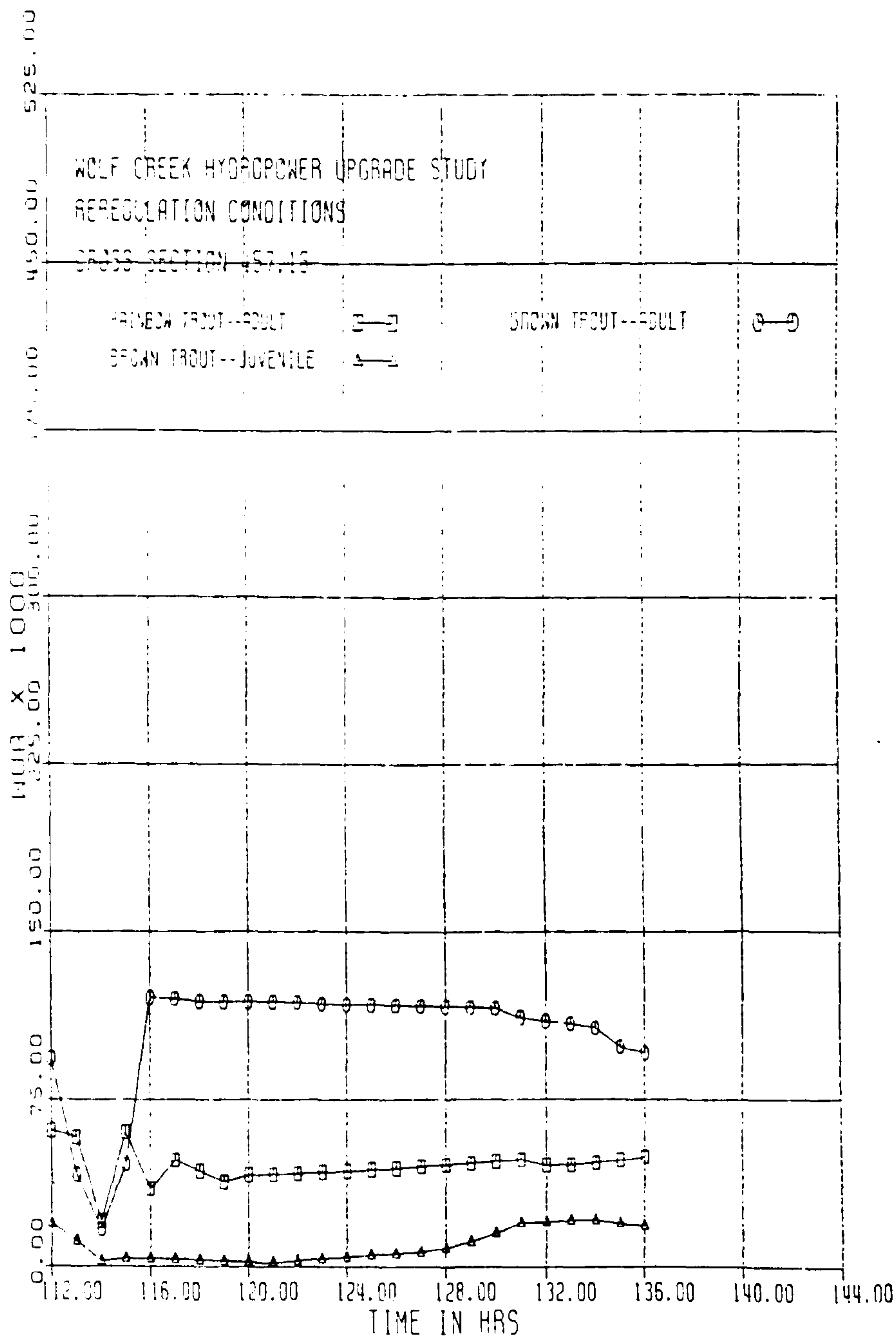


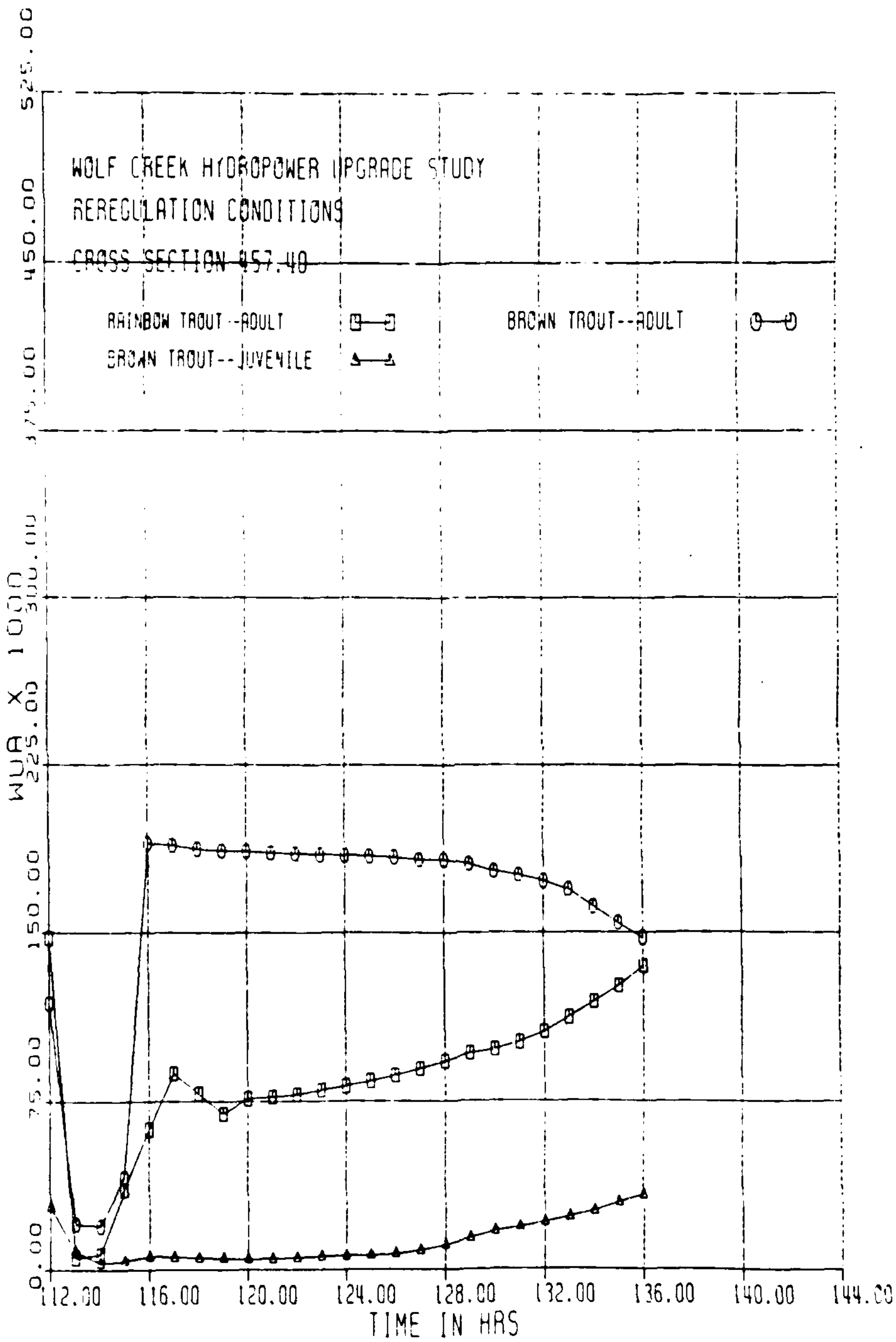
WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 454.70
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA x 1000
0.00
75.00
150.00
225.00
300.00
450.00
525.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00
140.00
144.00
TIME IN HRS

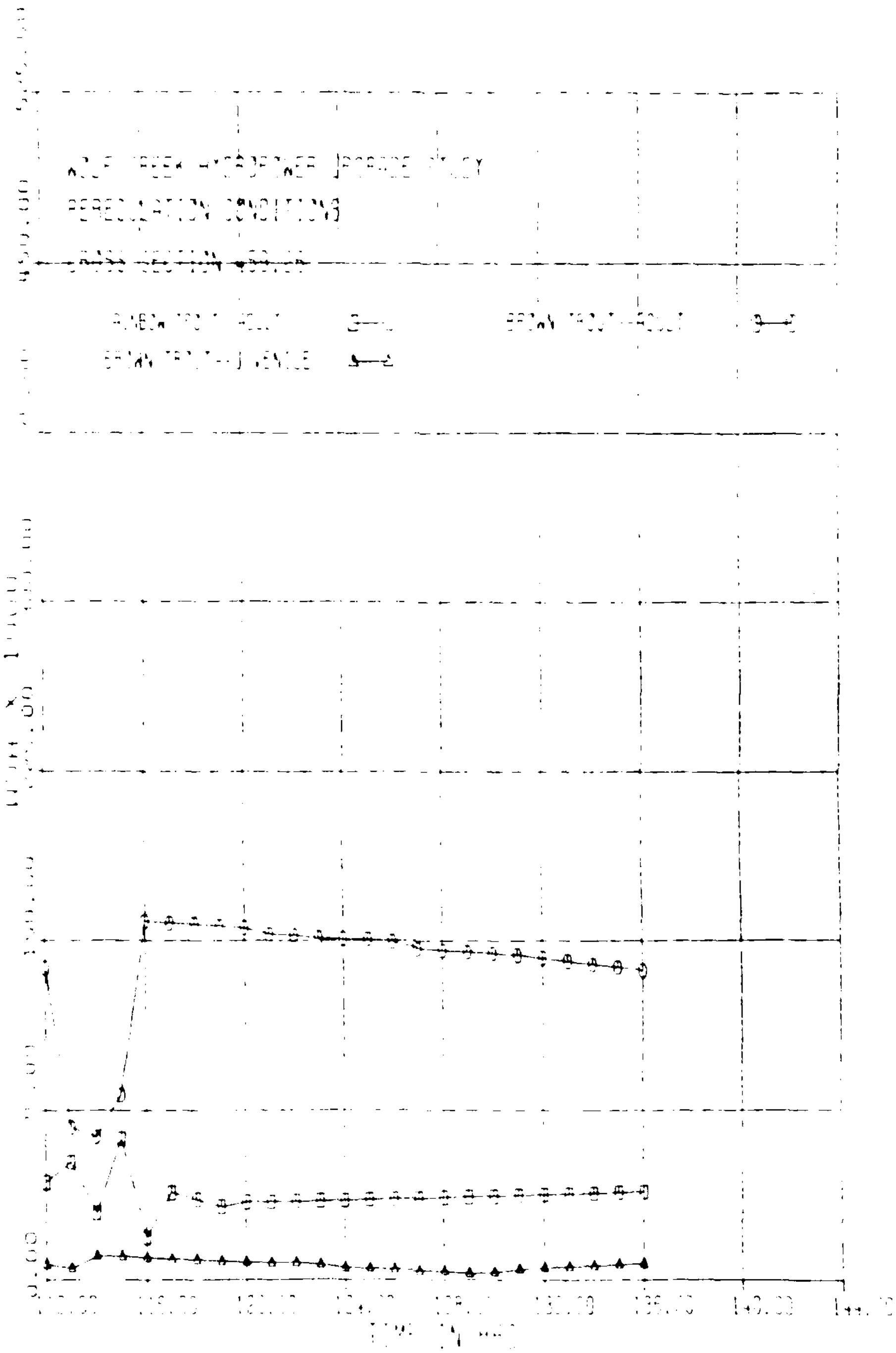

WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 155.10
RAINBOW TROUT--ADULT
BROWN TROUT--JUVENILE
BROWN TROUT--ADULT
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00
140.00
144.00
TIME IN HRS



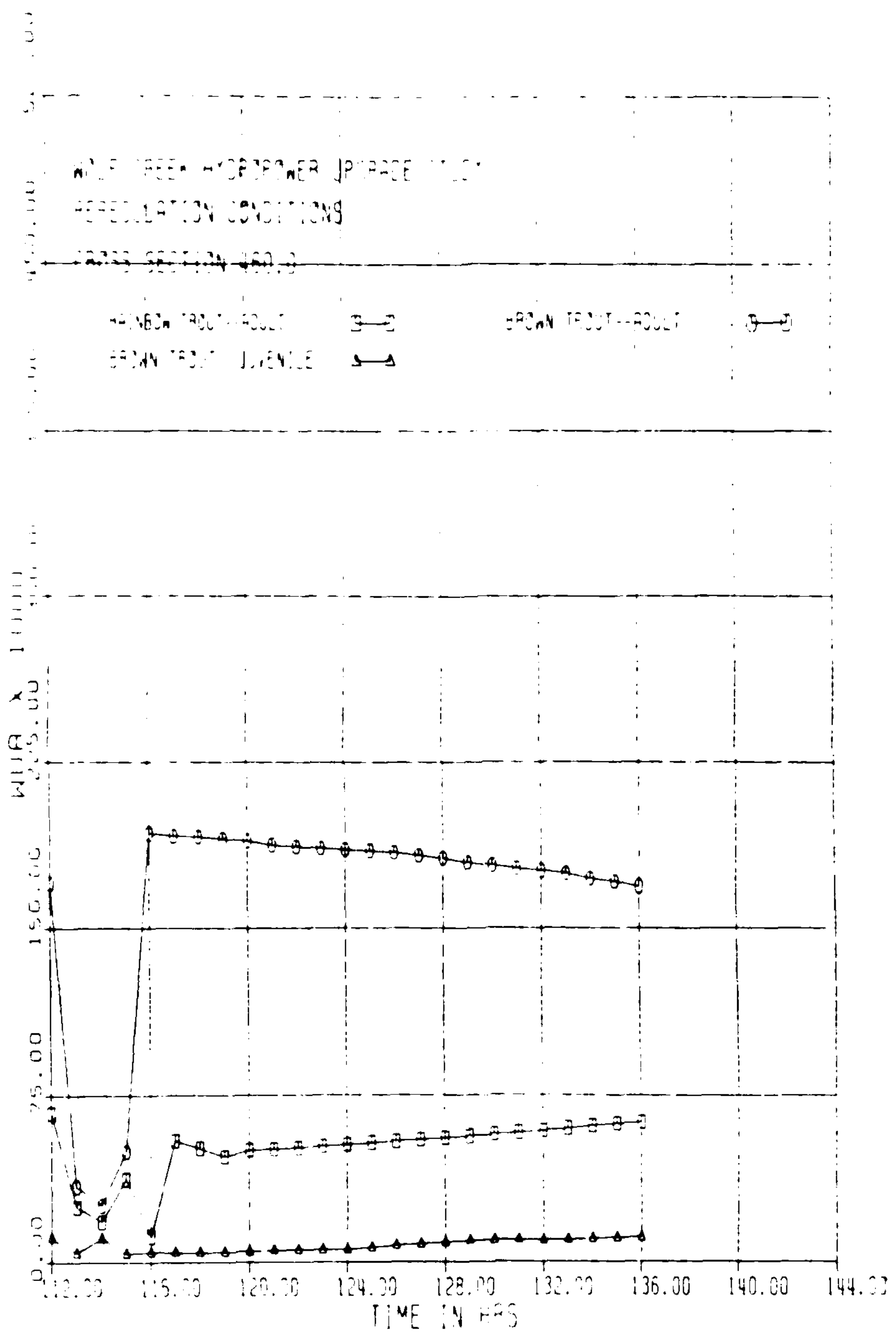
WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 155.00
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
375.00
450.00
525.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00
140.00
144.00
TIME IN HRS


WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
TIME IN HRS
0.00
75.00
150.00
225.00
300.00
450.00
525.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00
140.00
144.00


WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 457.40
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
0.00
75.00
150.00
225.00
300.00
450.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00
140.00
144.00
TIME IN HRS



PREREGULATION CONDITIONS
RAINBOW TROUT-ADULT
BROWN TROUT-ADULT
BROWN TROUT-JUVENILE



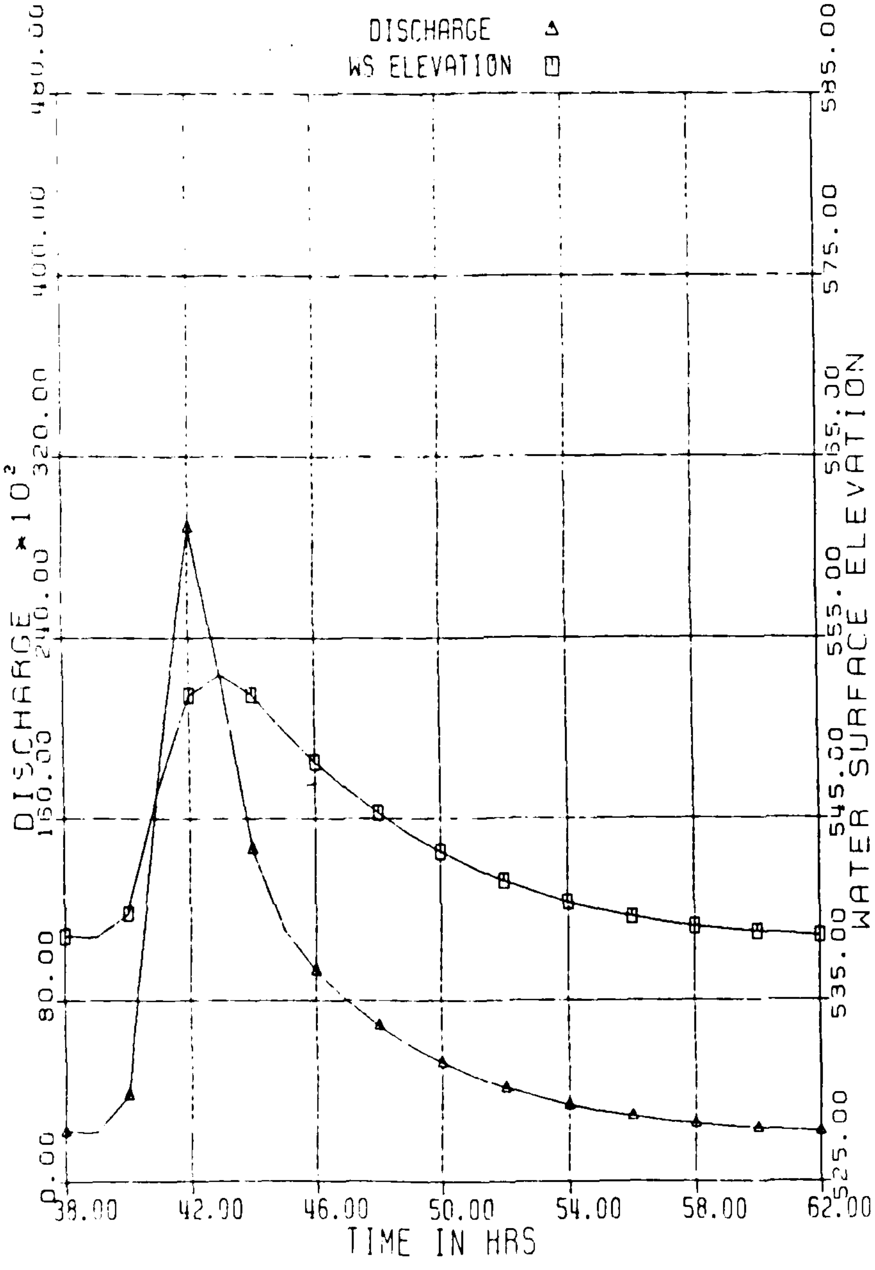
WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
RAINBOW TROUT--ADULT
BROWN TROUT--ADULT
BROWN TROUT--JUVENILE
WUA X 1000
TIME IN HRS

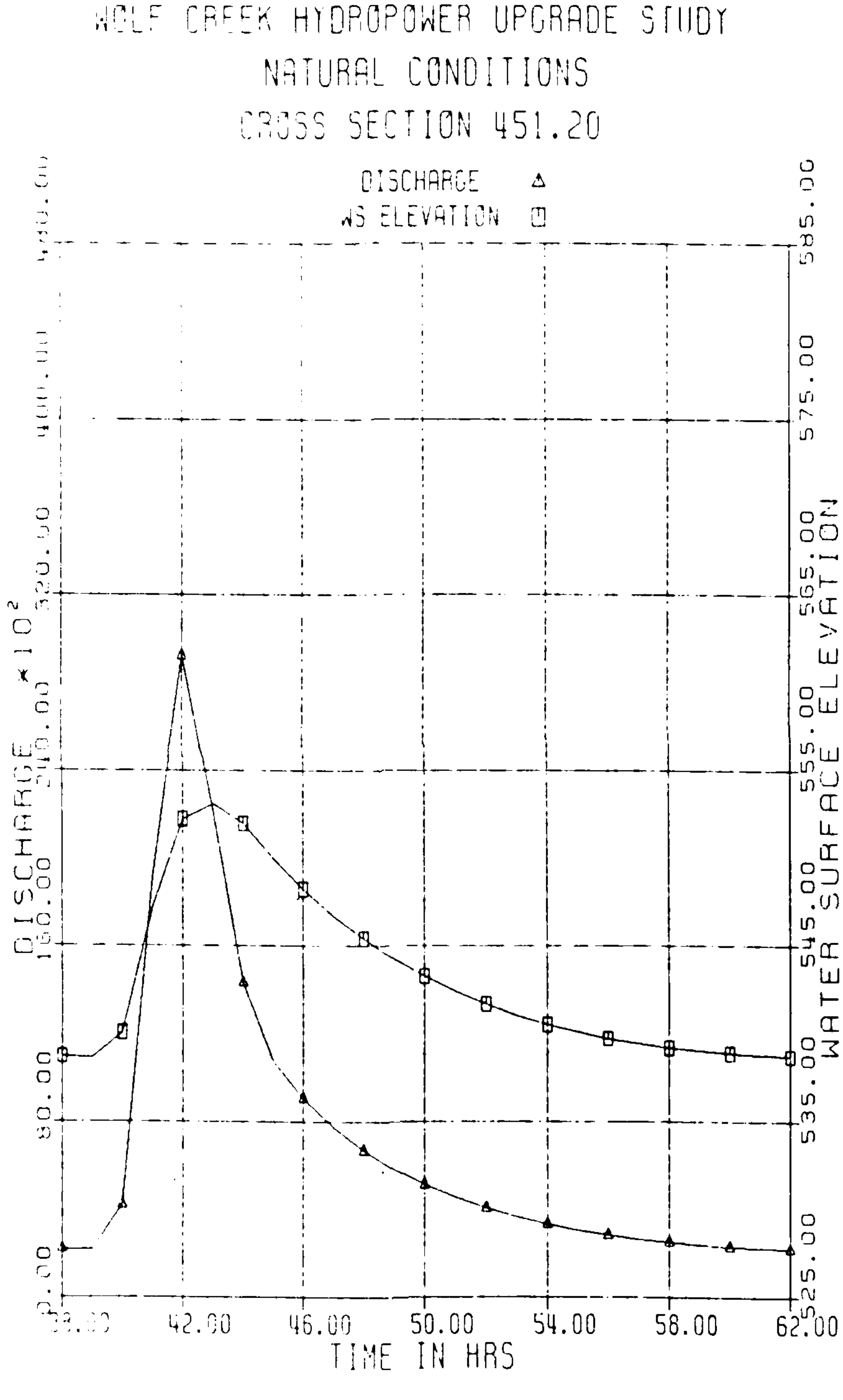
APPENDIX D: CROSS-SECTION PLOTS OF DISCHARGE VERSUS TIME AND WATER SURFACE ELEVATION VERSUS TIME UNDER NONREREGULATION (NATURAL) AND REREGULATION CONDITIONS (hour 38 corresponds to 2:00 p.m. Thursday; hour 112 corresponds to 4:00 p.m. Sunday)

WOLF CREEK HYDROPOWER UPGRADE STUDY

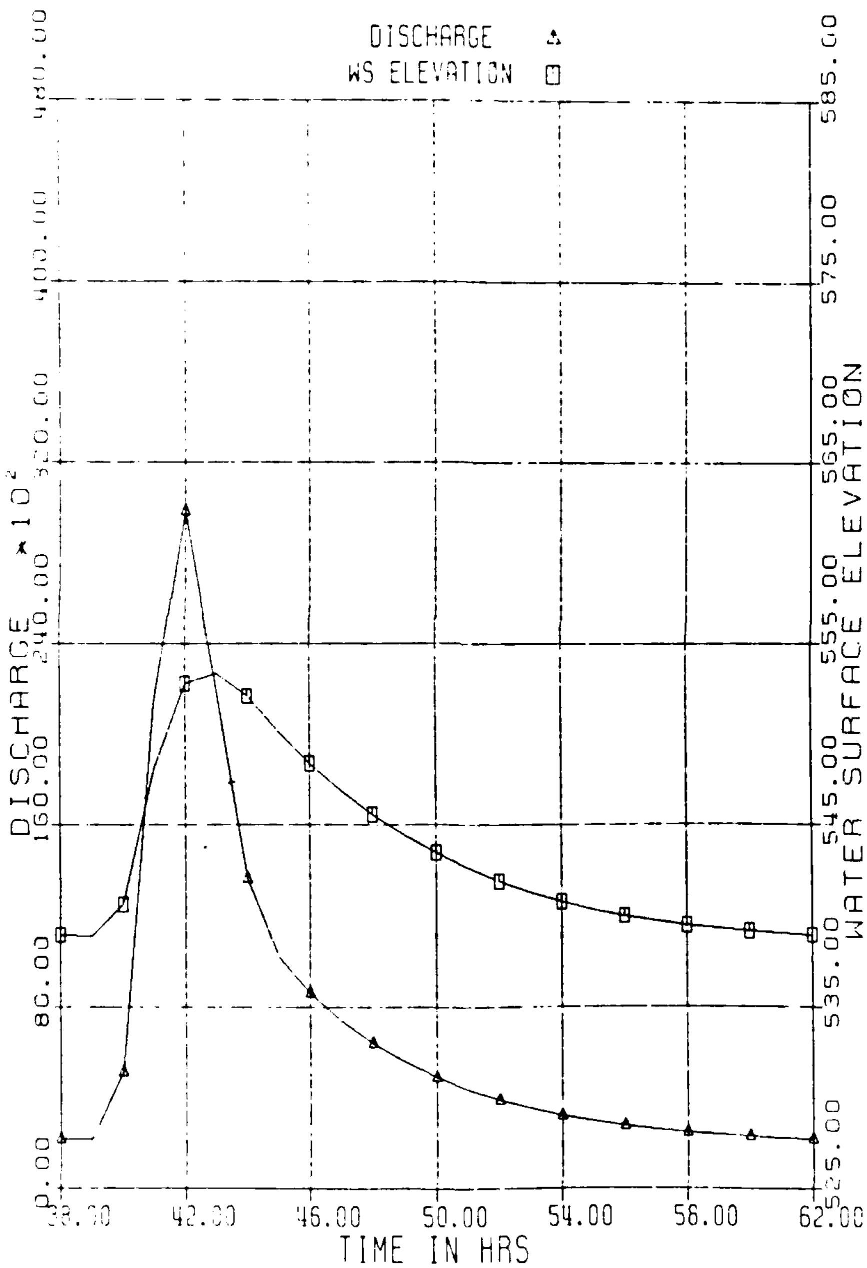
NATURAL CONDITIONS

CROSS SECTION 450.95

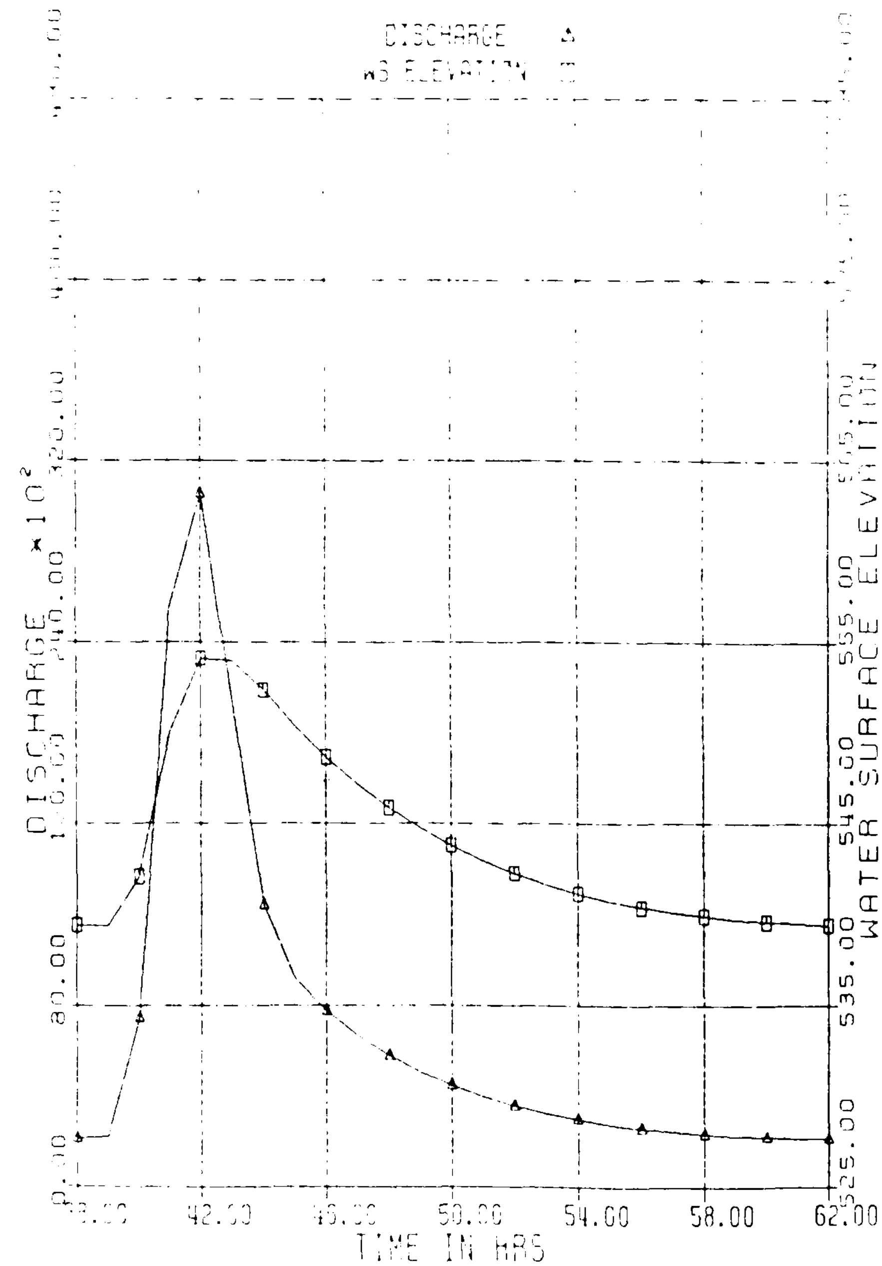


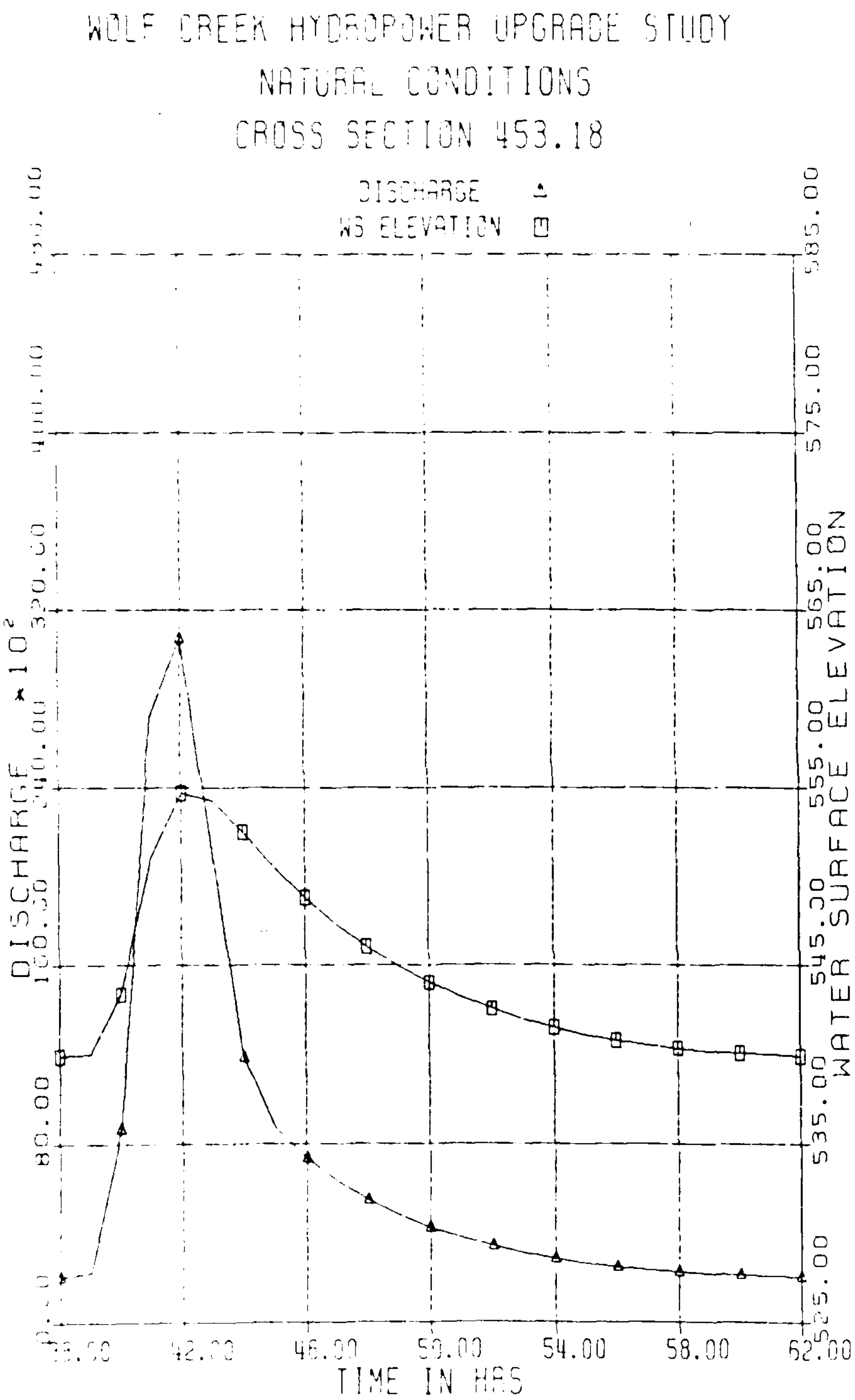

WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 451.20
DISCHARGE
WS ELEVATION
DISCHARGE $\times 10^2$
WATER SURFACE ELEVATION
TIME IN HRS
42.00
46.00
50.00
54.00
58.00
62.00
80.00
160.00
320.00
400.00
525.00
535.00
545.00
555.00
565.00
575.00
585.00

WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 451.70

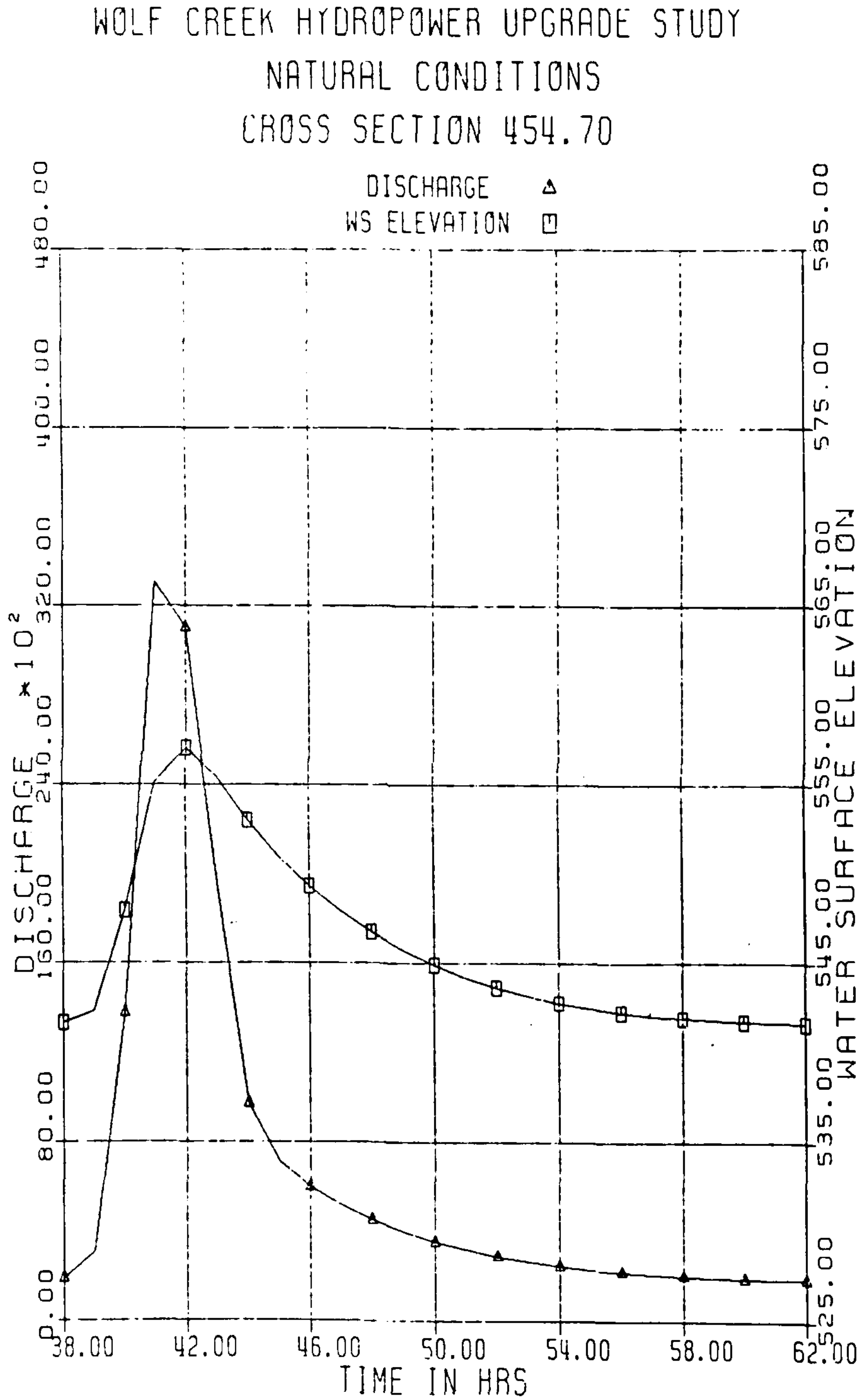


WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 452.76



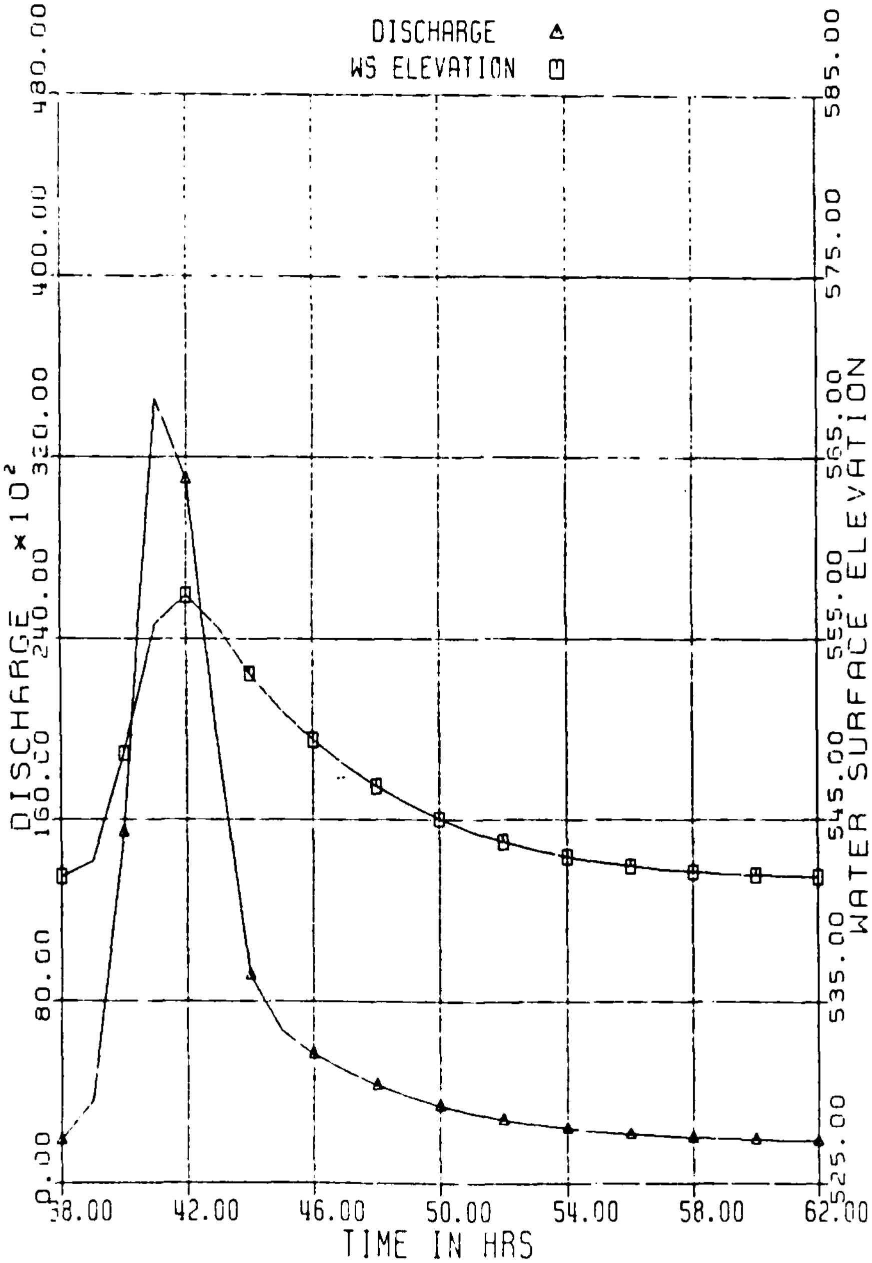


WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 453.18
DISCHARGE
WS ELEVATION
DISCHARGE ×10²
WATER SURFACE ELEVATION
TIME IN HRS
585.00
575.00
565.00
555.00
545.00
535.00
525.00
320.00
160.00
80.00
42.00
46.00
50.00
54.00
58.00
62.00

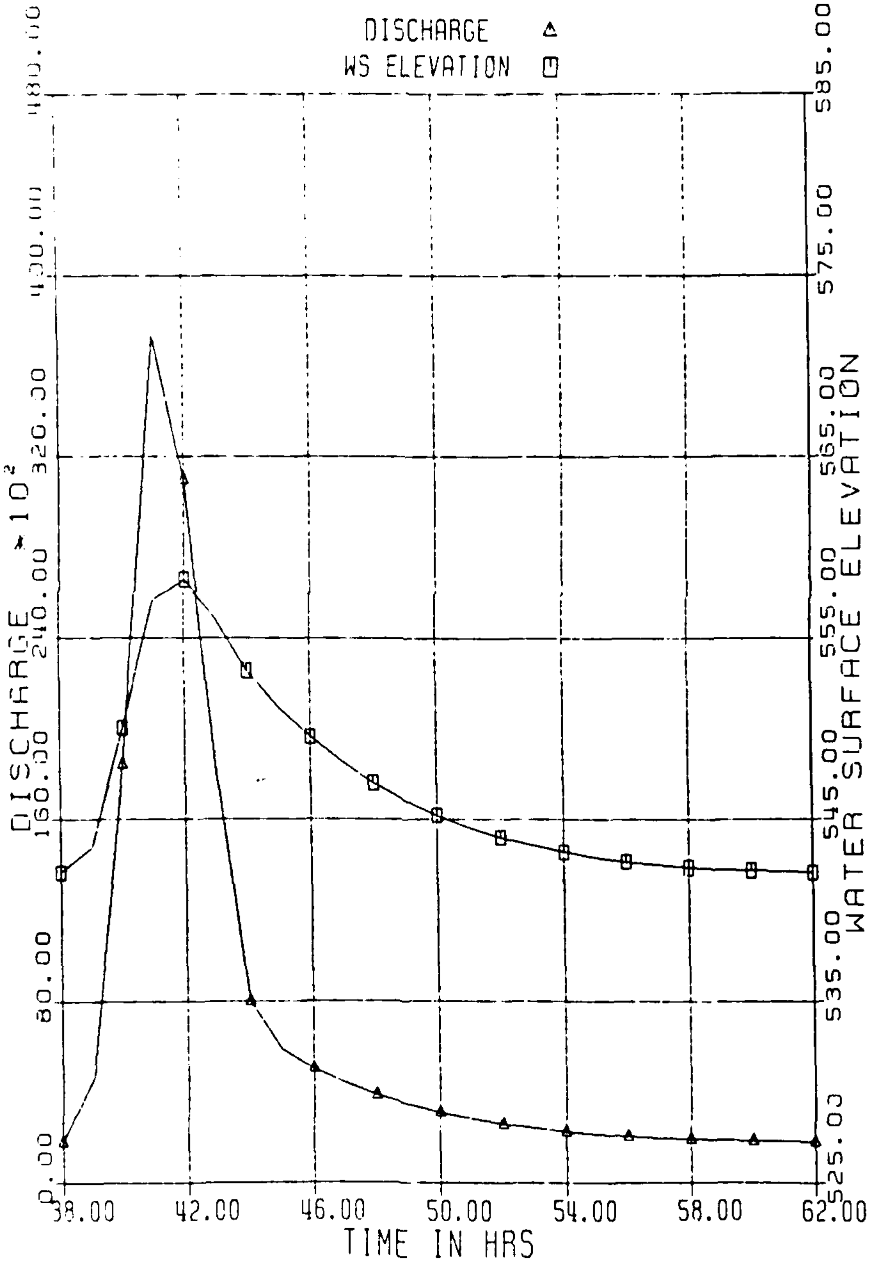


WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 454.70
DISCHARGE
WS ELEVATION
DISCHARGE *10²
WATER SURFACE ELEVATION
TIME IN HRS
0.00
80.00
160.00
240.00
320.00
400.00
480.00
525.00
535.00
545.00
555.00
565.00
575.00
585.00
38.00
42.00
46.00
50.00
54.00
58.00
62.00

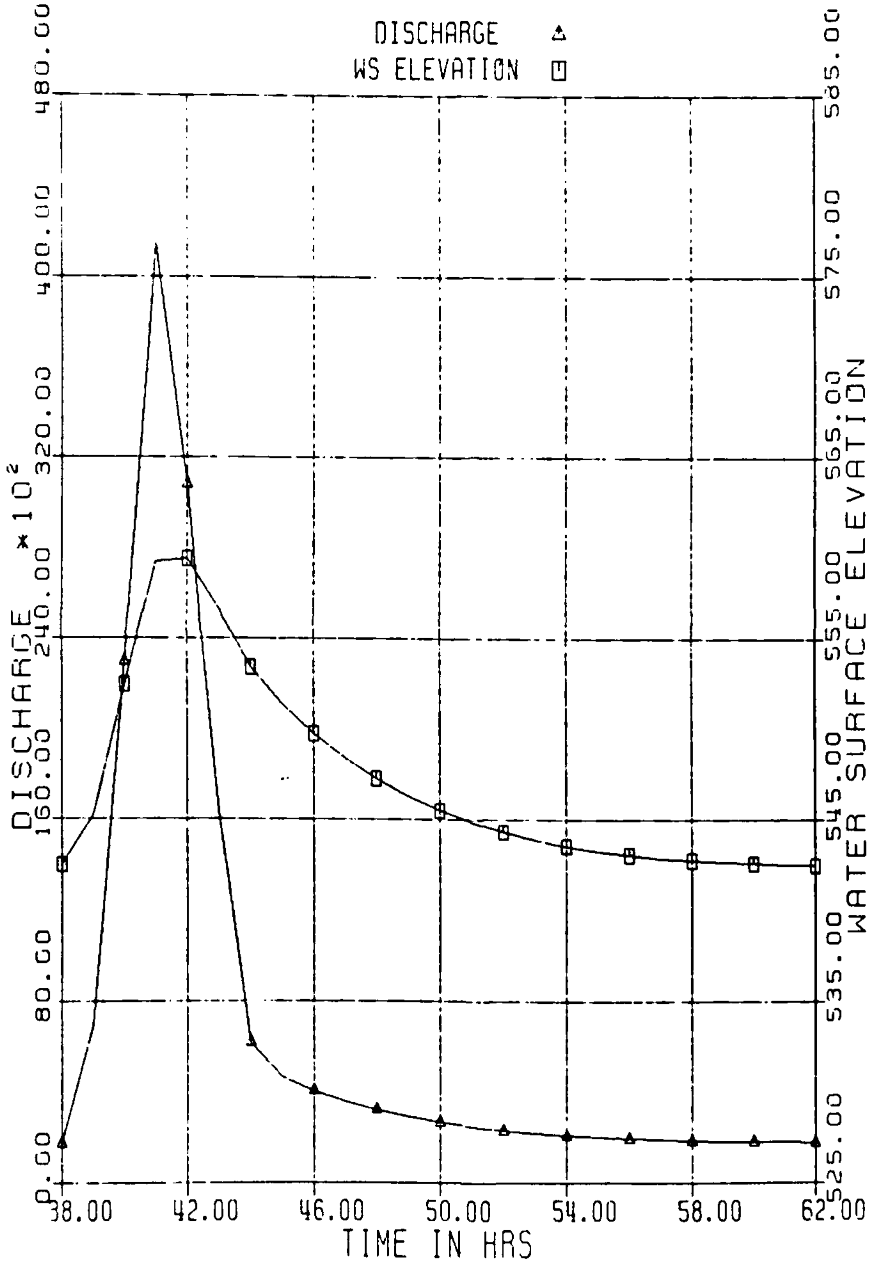
WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 455.10



WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 455.90



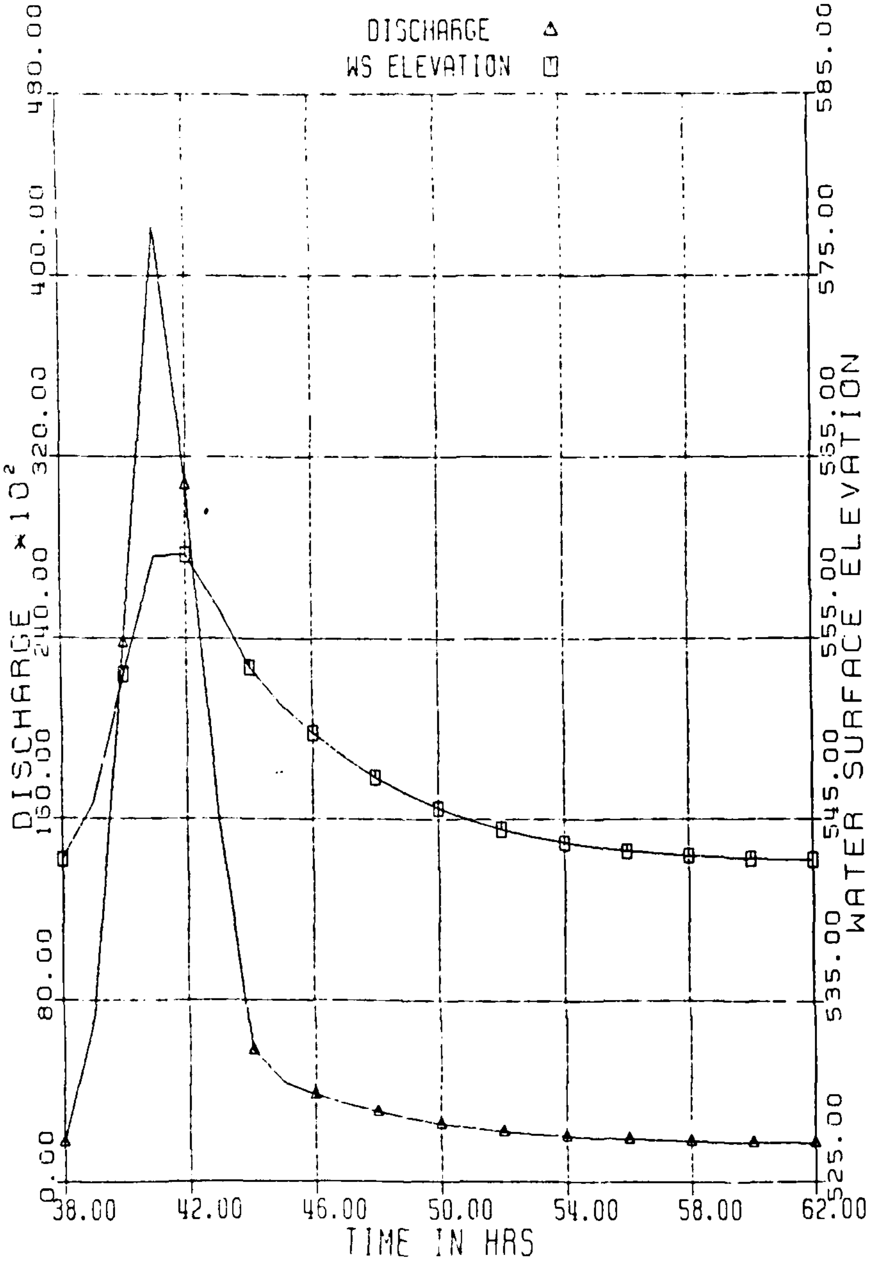
WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 457.16

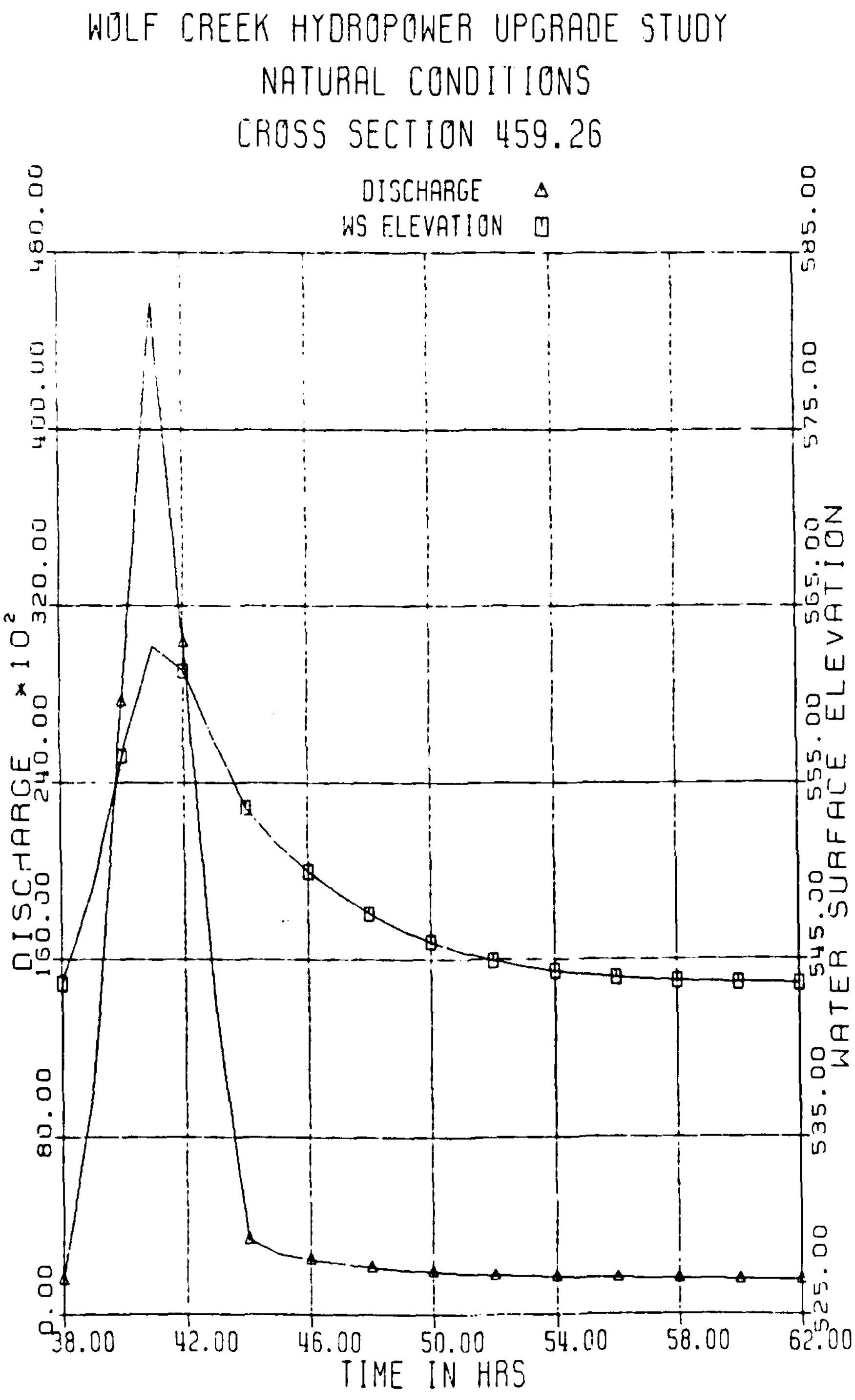


WOLF CREEK HYDROPOWER UPGRADE STUDY

NATURAL CONDITIONS

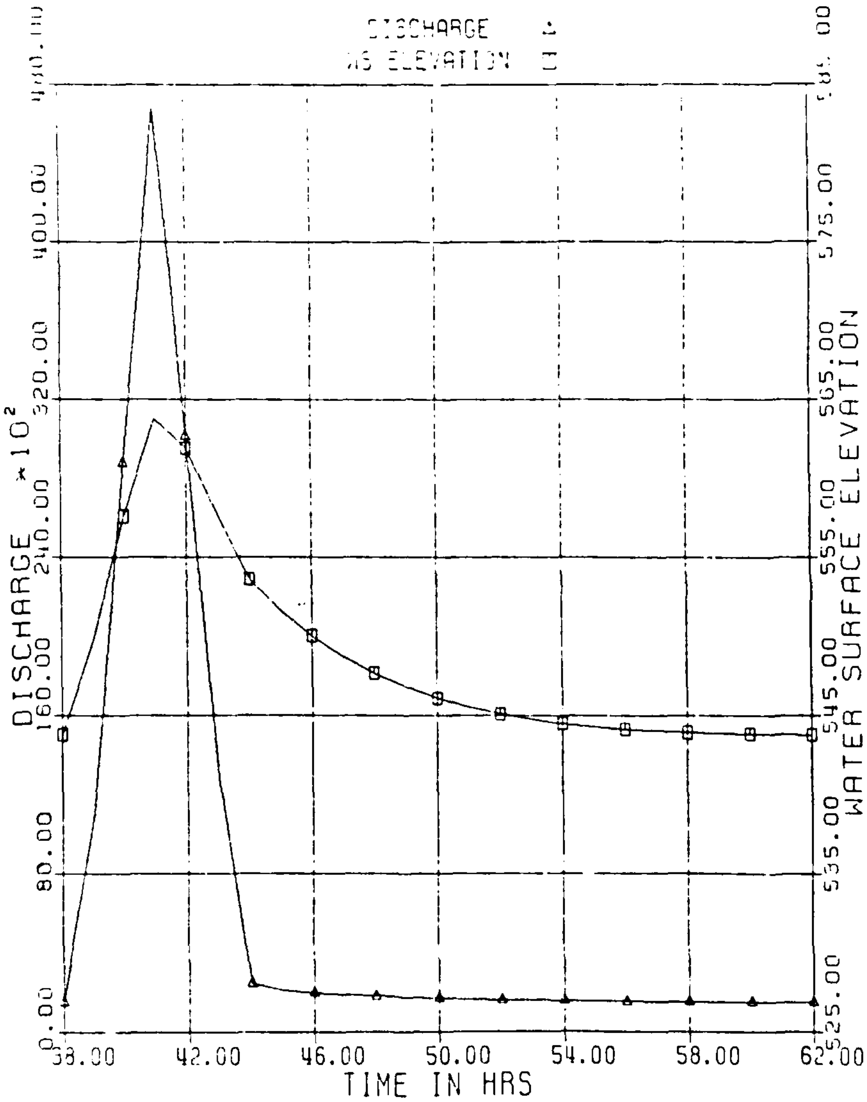
CROSS SECTION 457.40



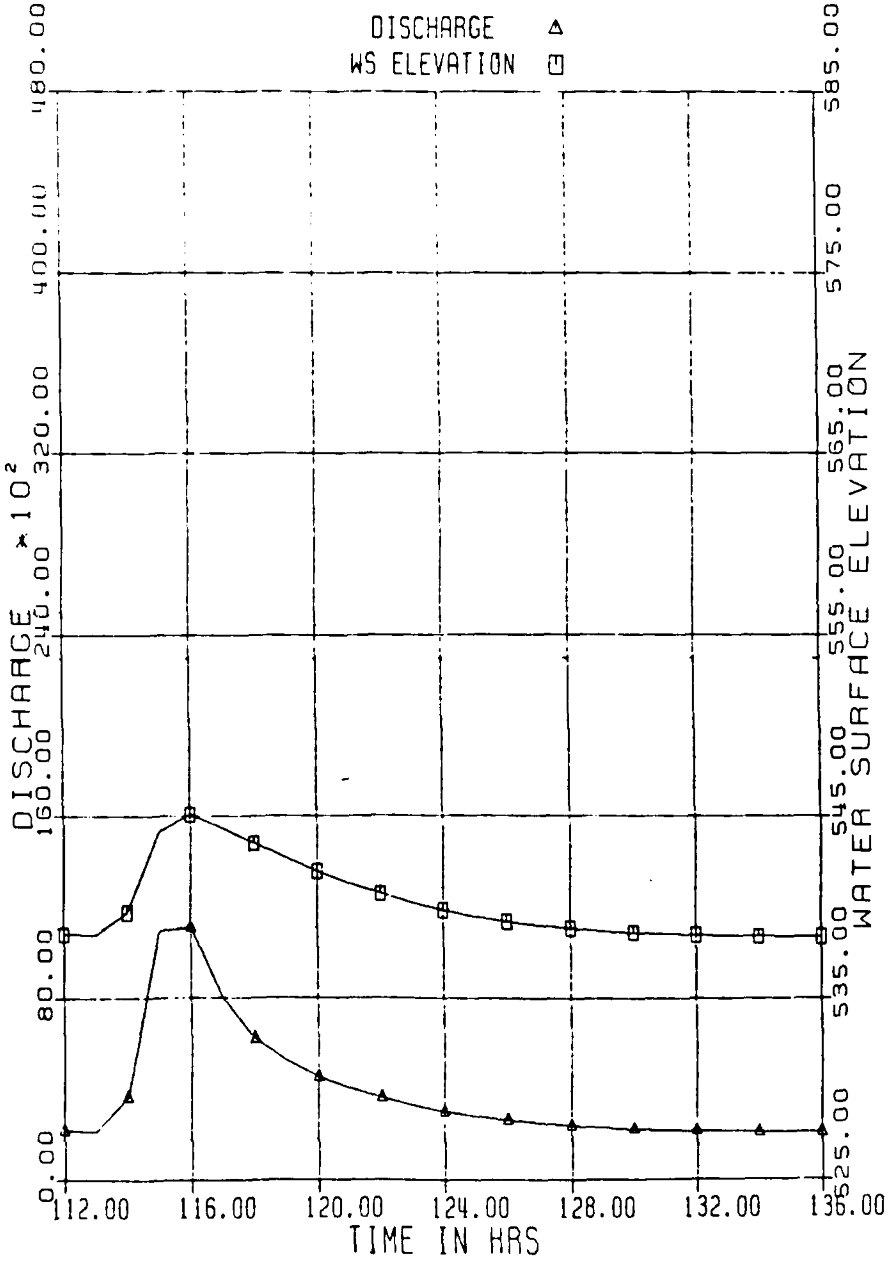


WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 459.26
DISCHARGE
WS ELEVATION
DISCHARGE *10²
WATER SURFACE ELEVATION
TIME IN HRS
0.00
80.00
160.00
240.00
320.00
400.00
480.00
525.00
535.00
545.00
555.00
565.00
575.00
585.00
38.00
42.00
46.00
50.00
54.00
58.00
62.00

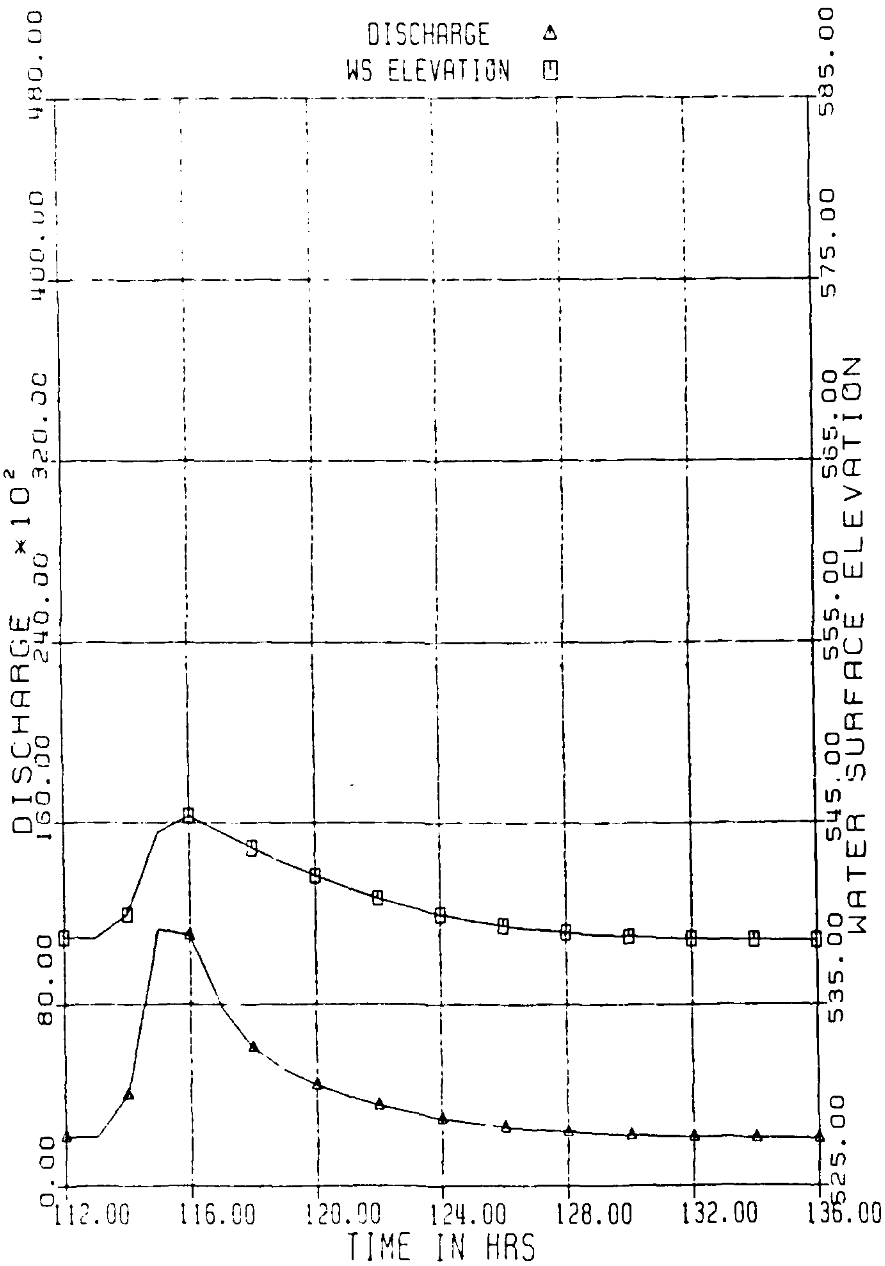
WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 460.00



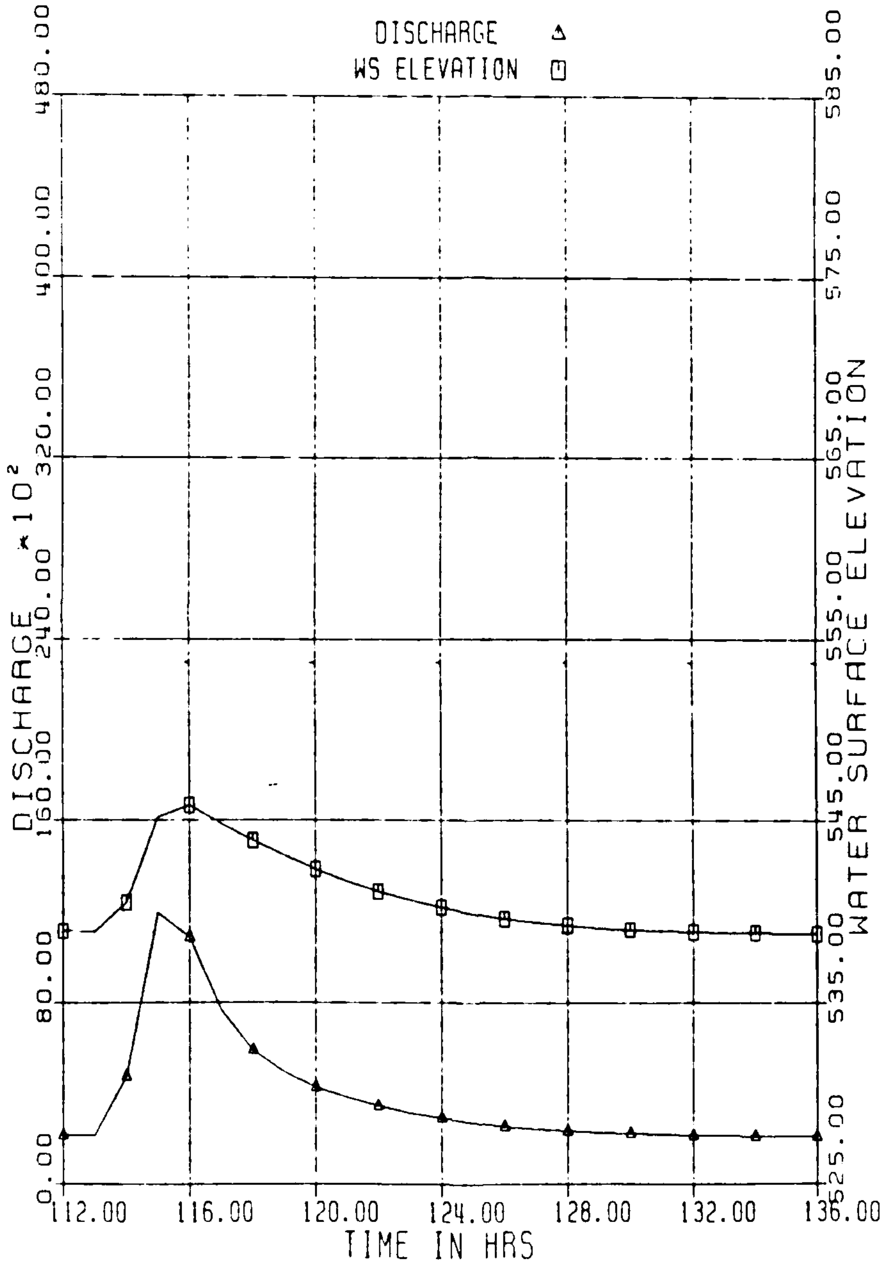
WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 450.95



WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 451.20



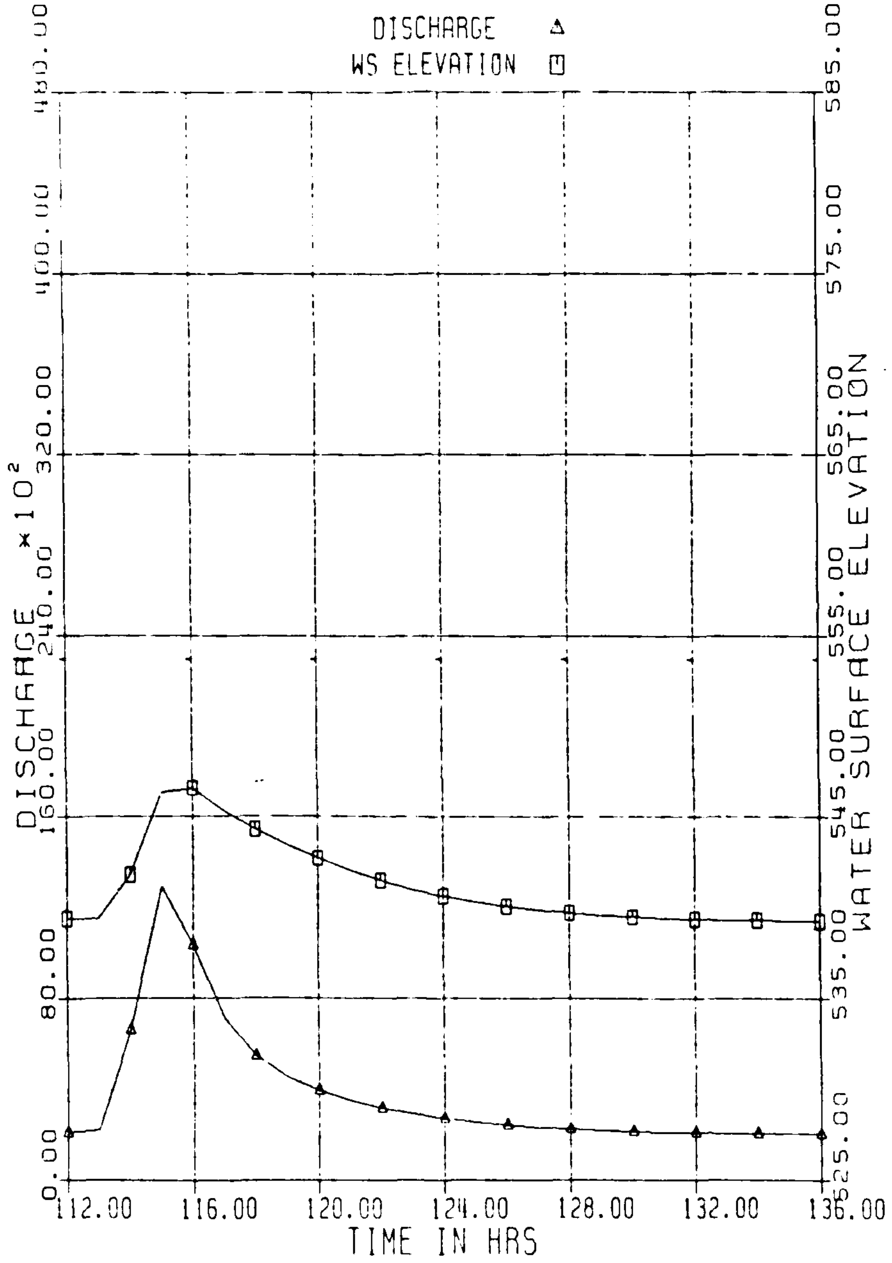
WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 451.70

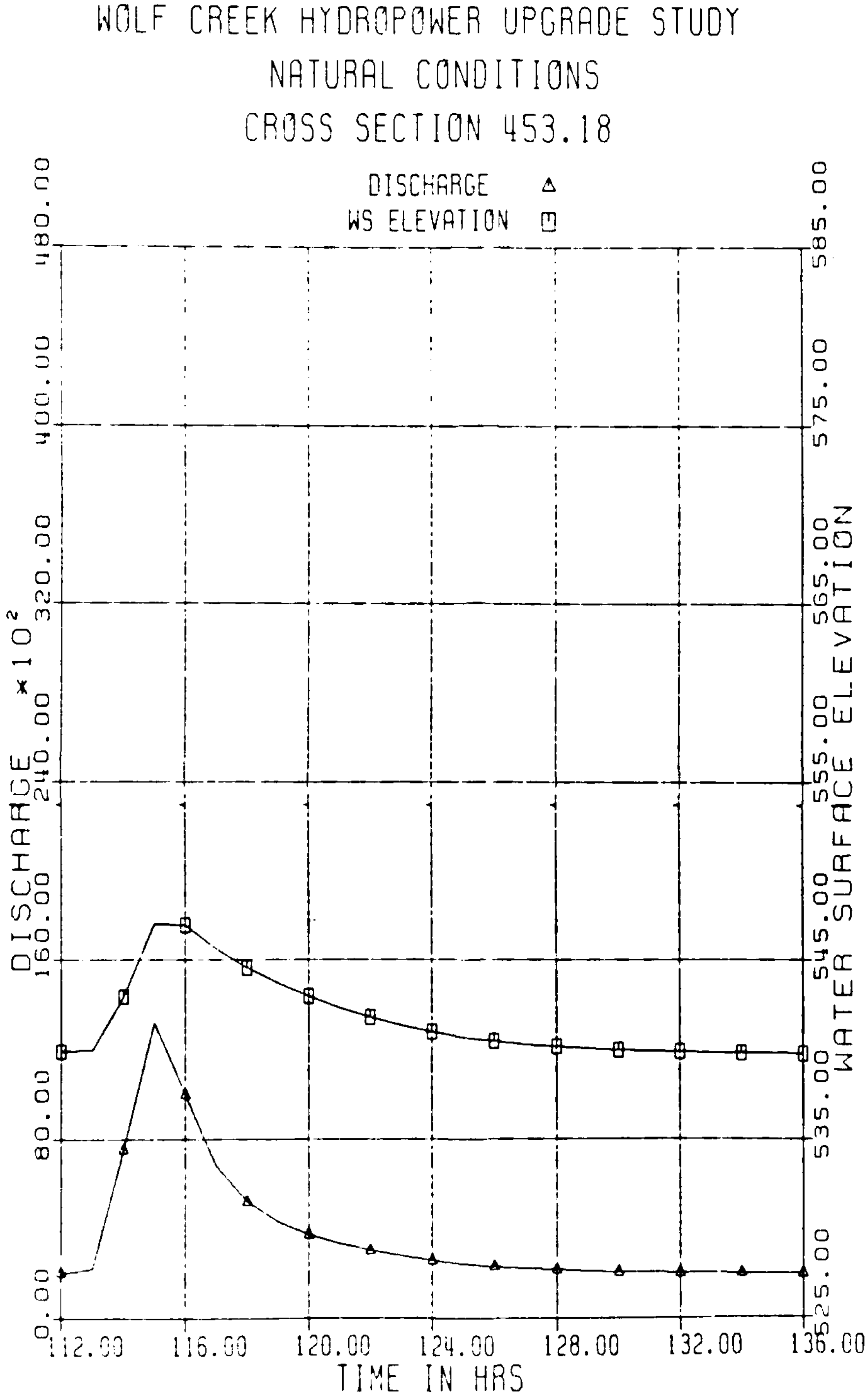


WOLF CREEK HYDROPOWER UPGRADE STUDY

NATURAL CONDITIONS

CROSS SECTION 452.76



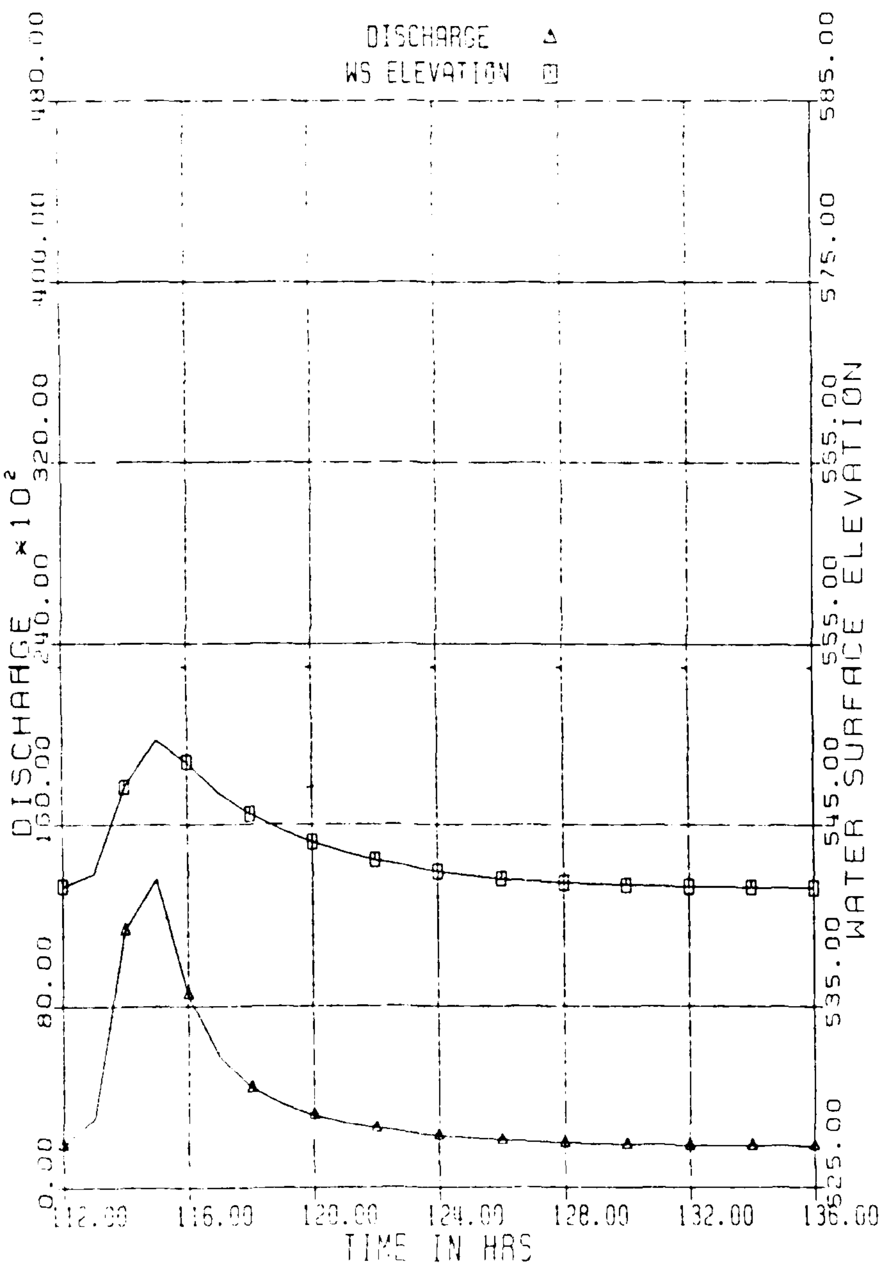


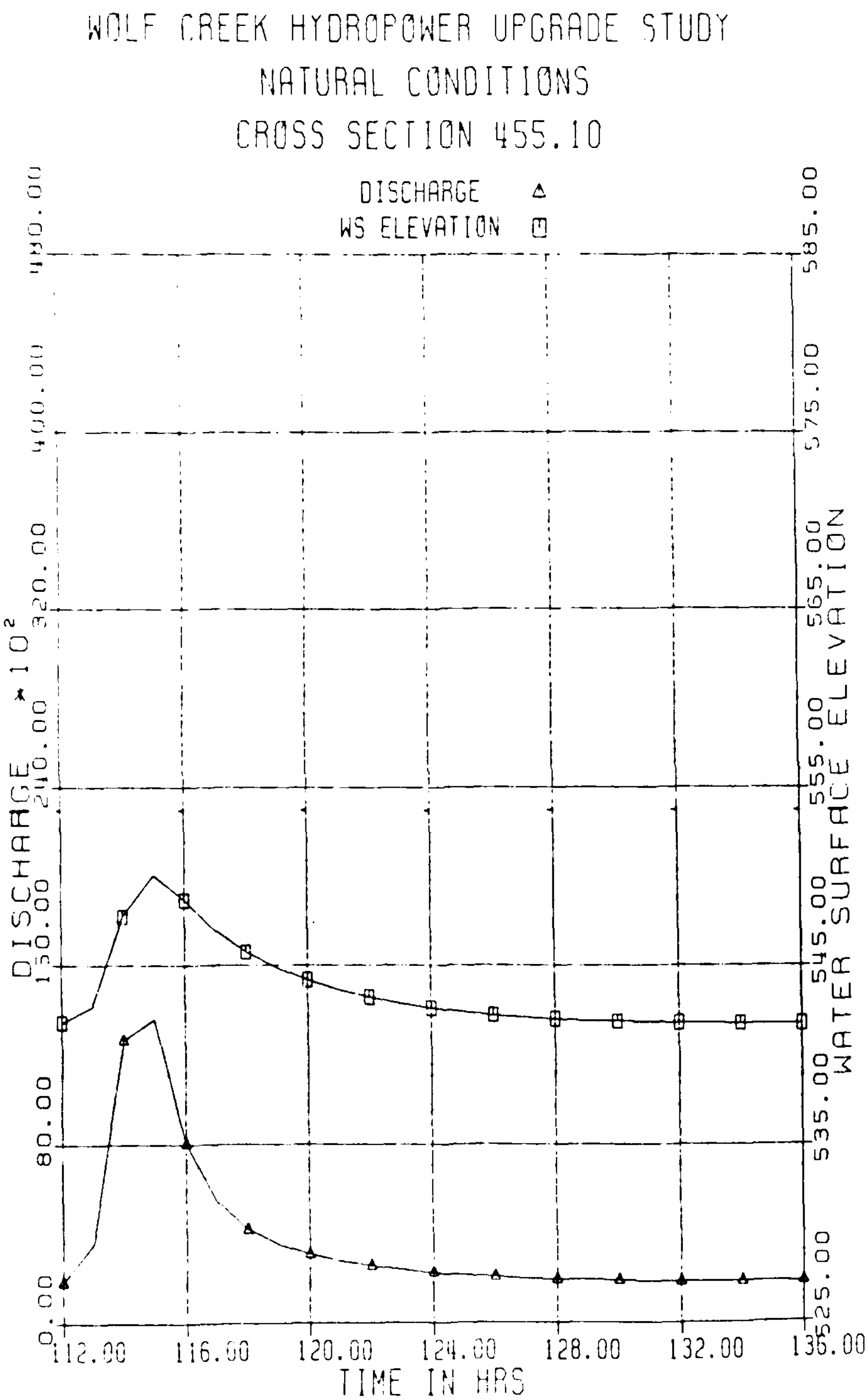
WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 453.18
DISCHARGE
WS ELEVATION
DISCHARGE ×10²
WATER SURFACE ELEVATION
TIME IN HRS
0.00
80.00
160.00
240.00
320.00
400.00
480.00
525.00
535.00
545.00
555.00
565.00
575.00
585.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00

WOLF CREEK HYDROPOWER UPGRADE STUDY

NATURAL CONDITIONS

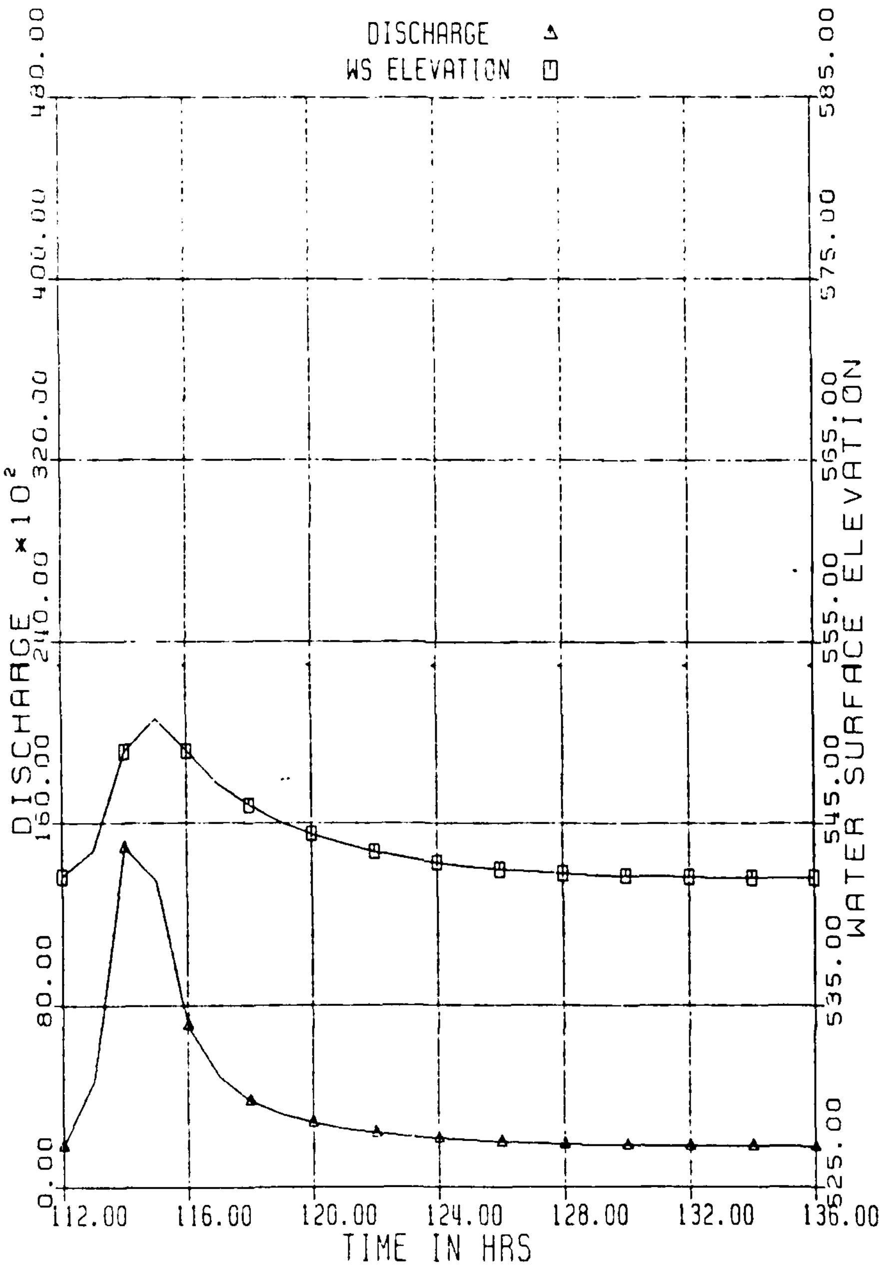
CROSS SECTION 454.70





WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 455.10
DISCHARGE
WS ELEVATION
DISCHARGE * 10²
WATER SURFACE ELEVATION
TIME IN HRS
0.00
80.00
160.00
240.00
320.00
400.00
480.00
525.00
535.00
545.00
555.00
565.00
575.00
585.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00

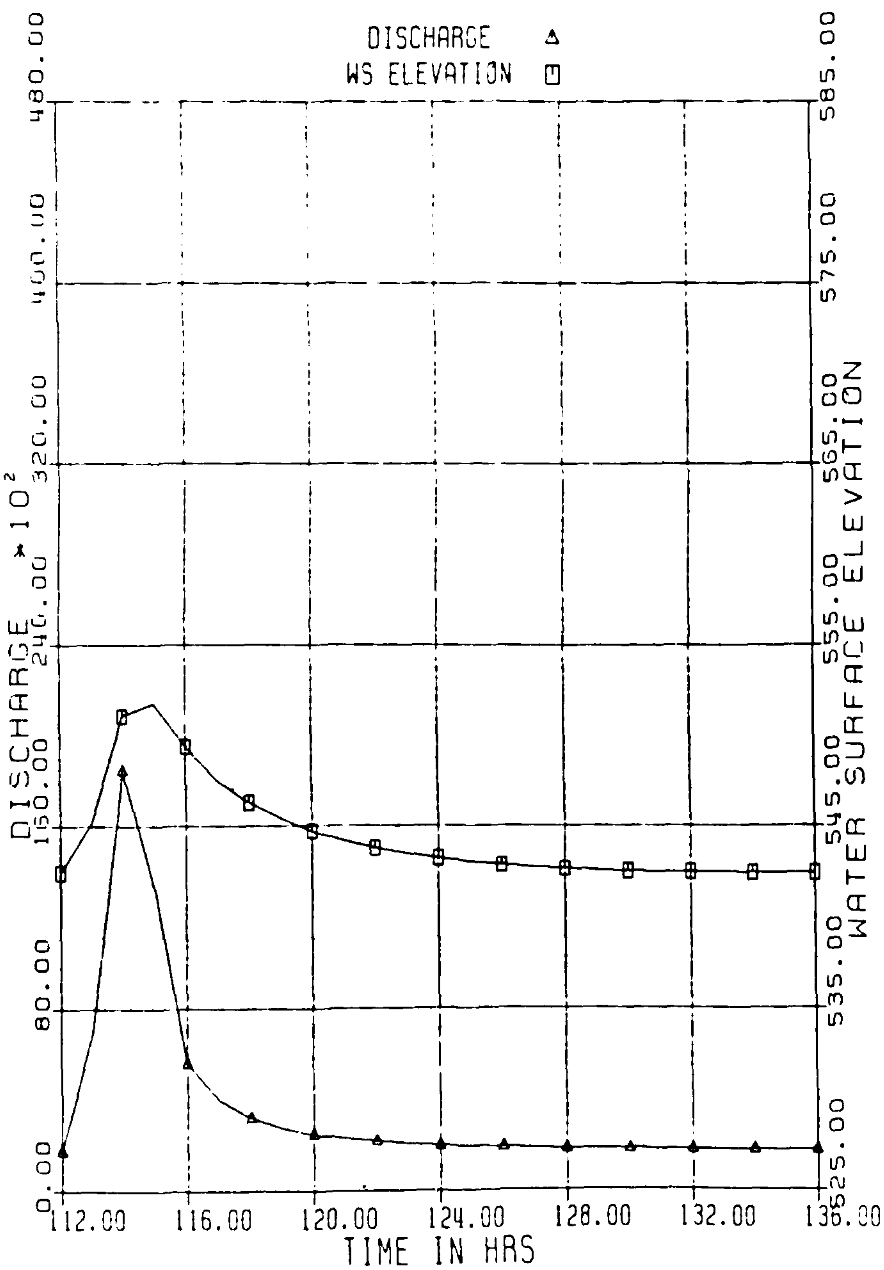
WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 455.90



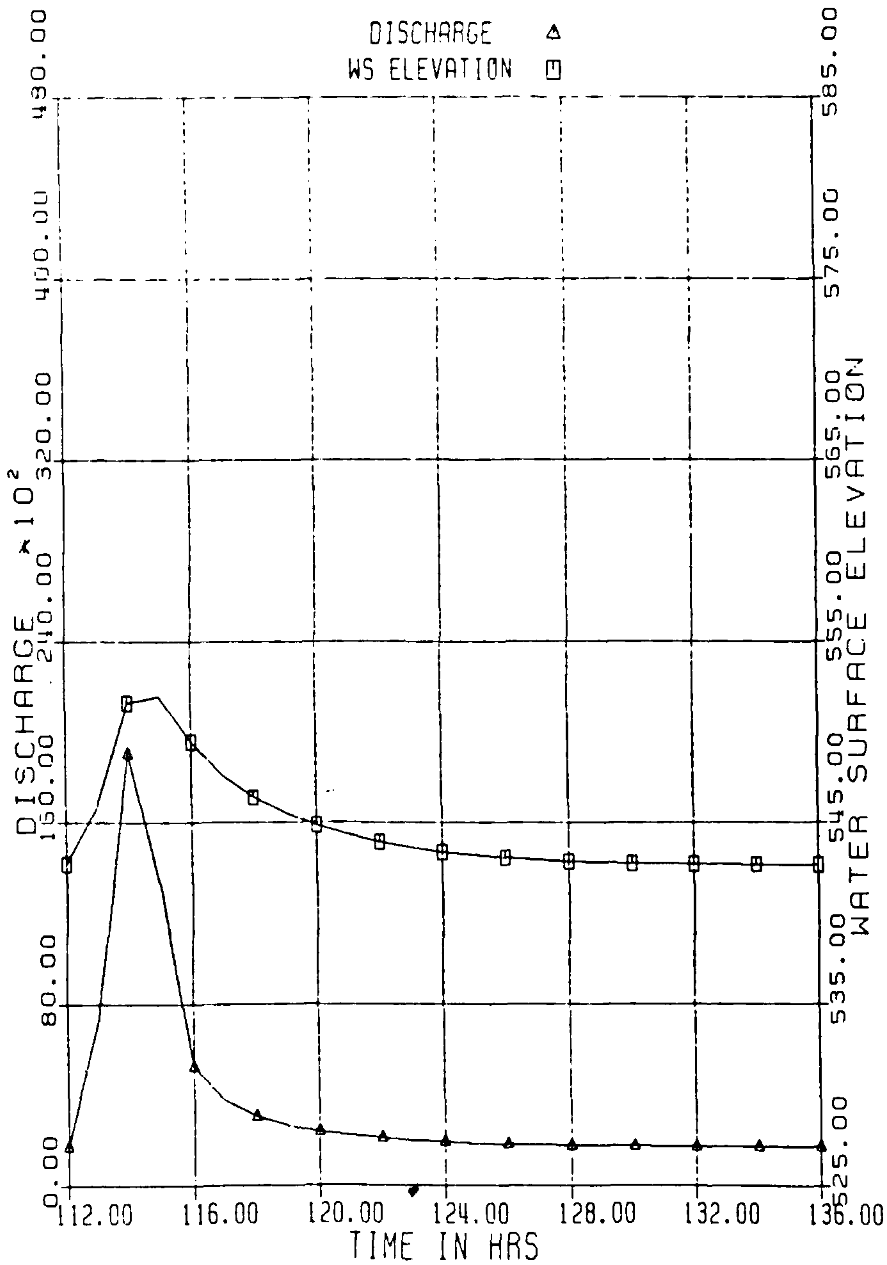
WOLF CREEK HYDROPOWER UPGRADE STUDY

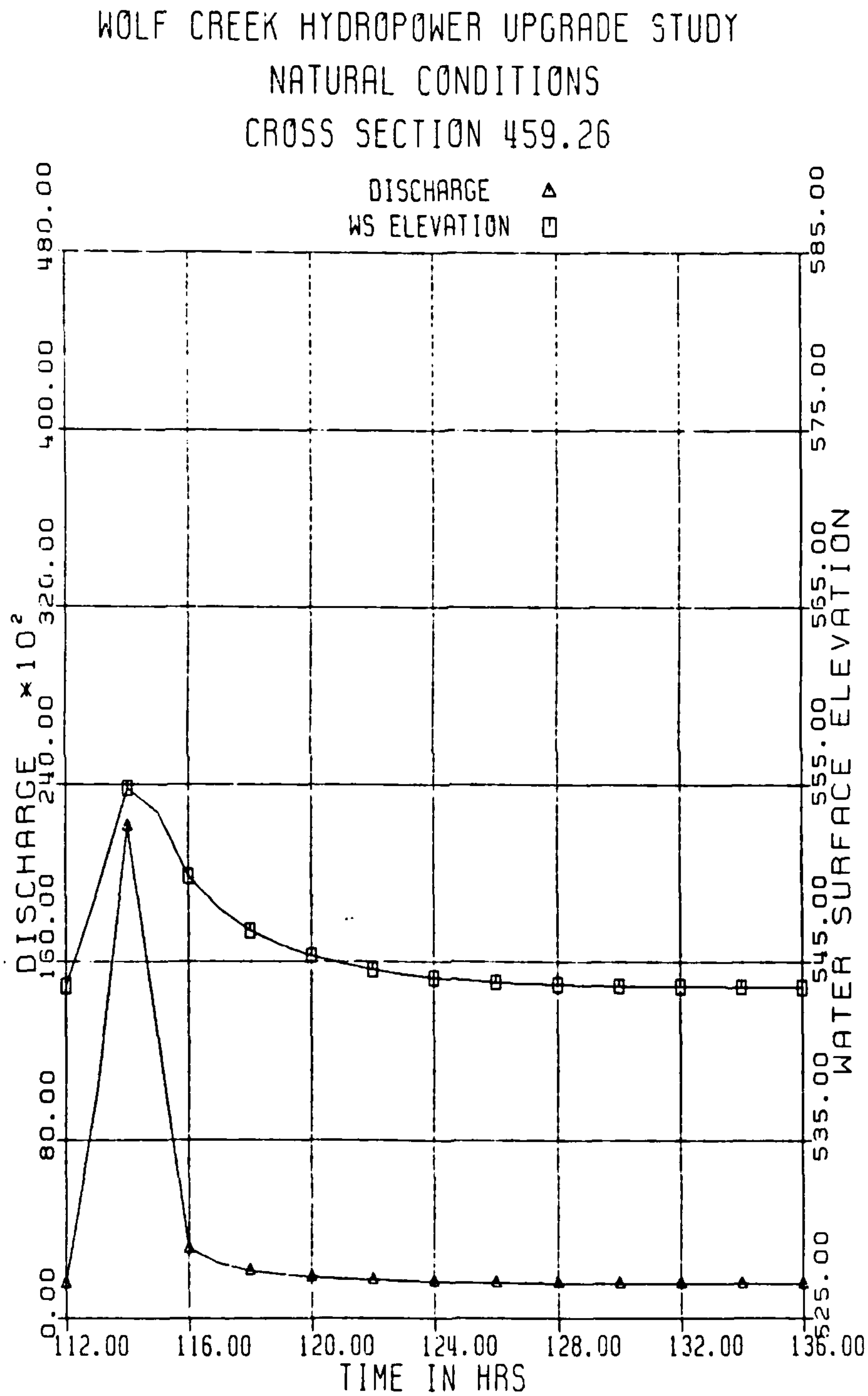
NATURAL CONDITIONS

CROSS SECTION 457.16



WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 457.40

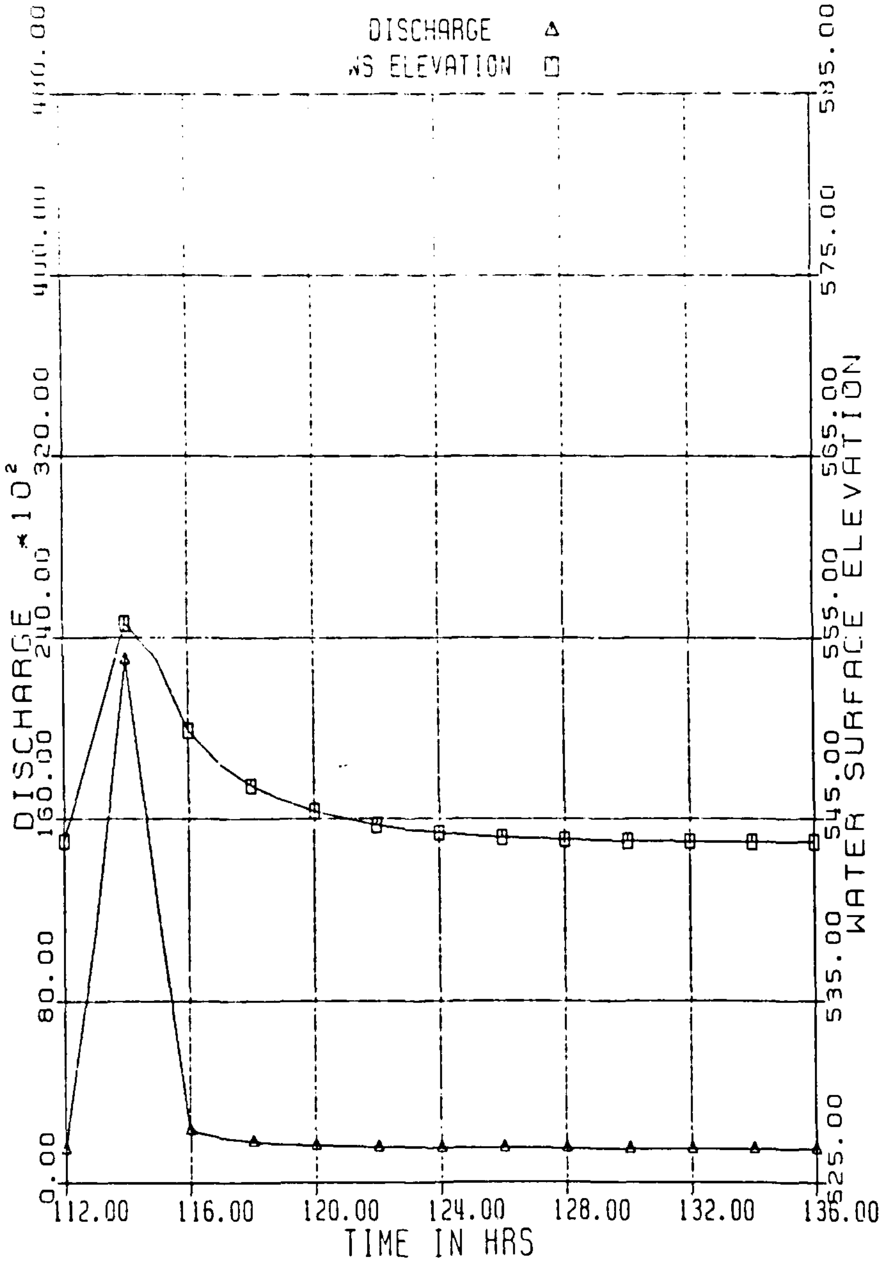


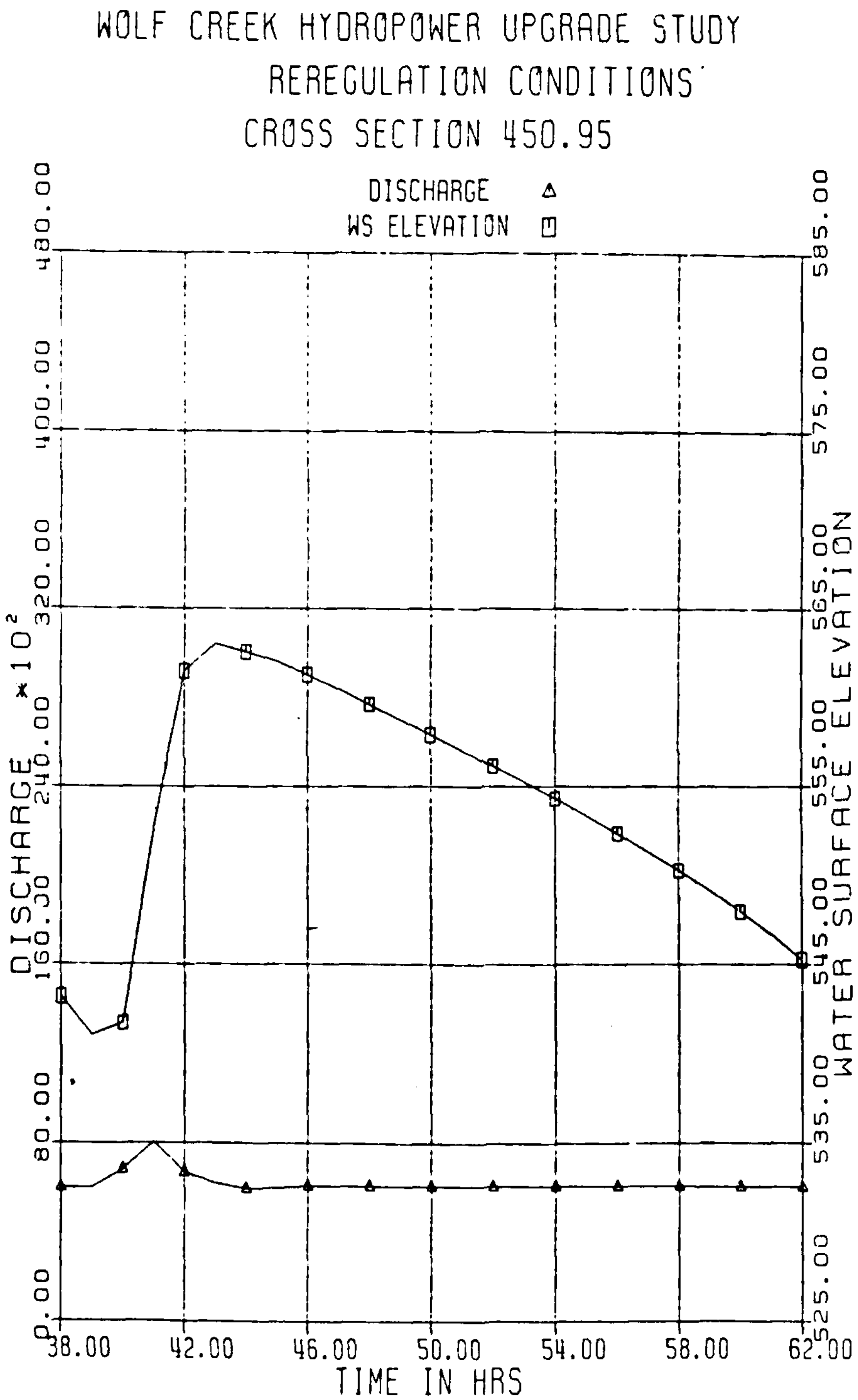

WOLF CREEK HYDROPOWER UPGRADE STUDY
NATURAL CONDITIONS
CROSS SECTION 459.26
DISCHARGE
WS ELEVATION
DISCHARGE ×10²
0.00
80.00
160.00
240.00
320.00
400.00
480.00
WATER SURFACE ELEVATION
525.00
535.00
545.00
555.00
565.00
575.00
585.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00
TIME IN HRS

WOLF CREEK HYDROPOWER UPGRADE STUDY

NATURAL CONDITIONS

CROSS SECTION 460.00



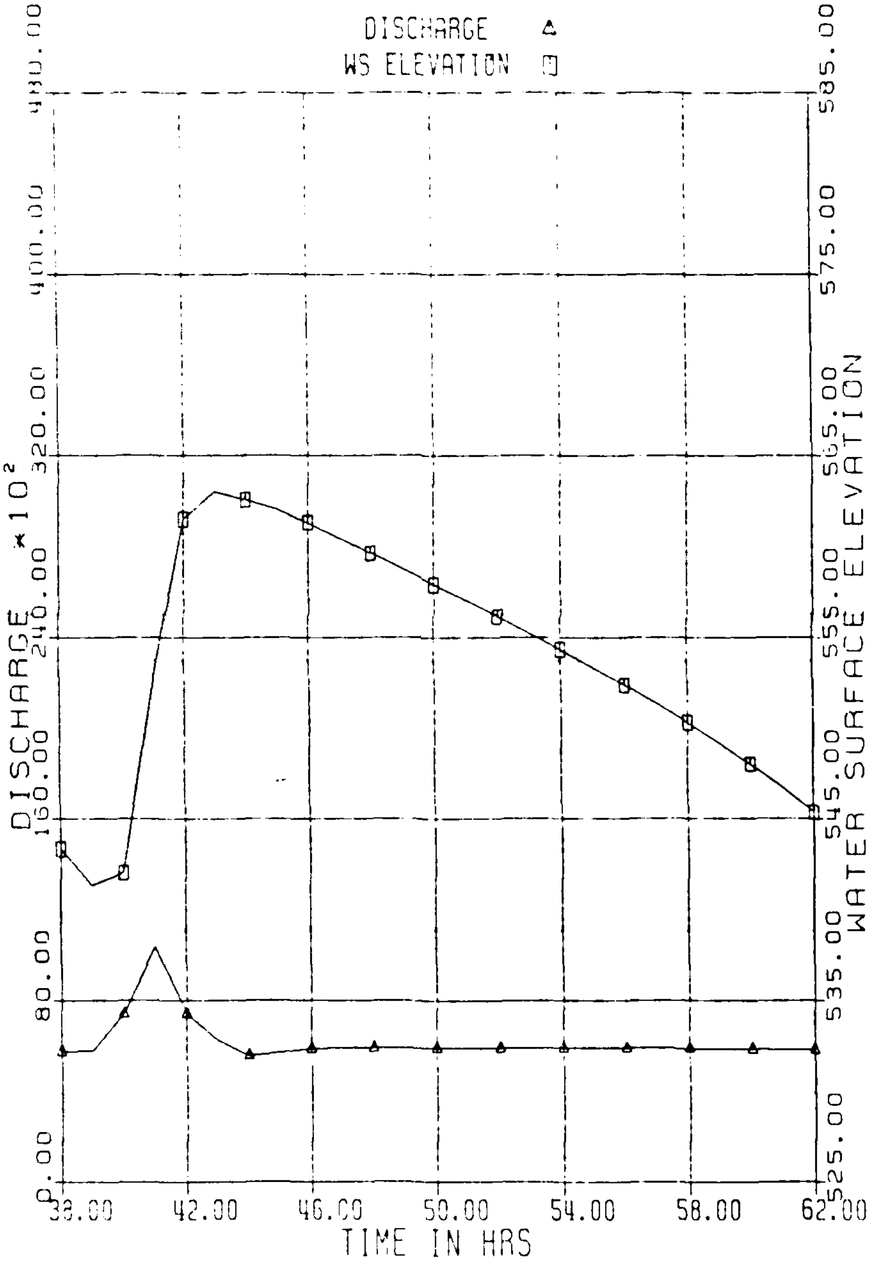


WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 450.95
DISCHARGE
WS ELEVATION
DISCHARGE *10²
WATER SURFACE ELEVATION
TIME IN HRS
0.00
80.00
160.00
240.00
320.00
400.00
480.00
525.00
535.00
545.00
555.00
565.00
575.00
585.00
38.00
42.00
46.00
50.00
54.00
58.00
62.00

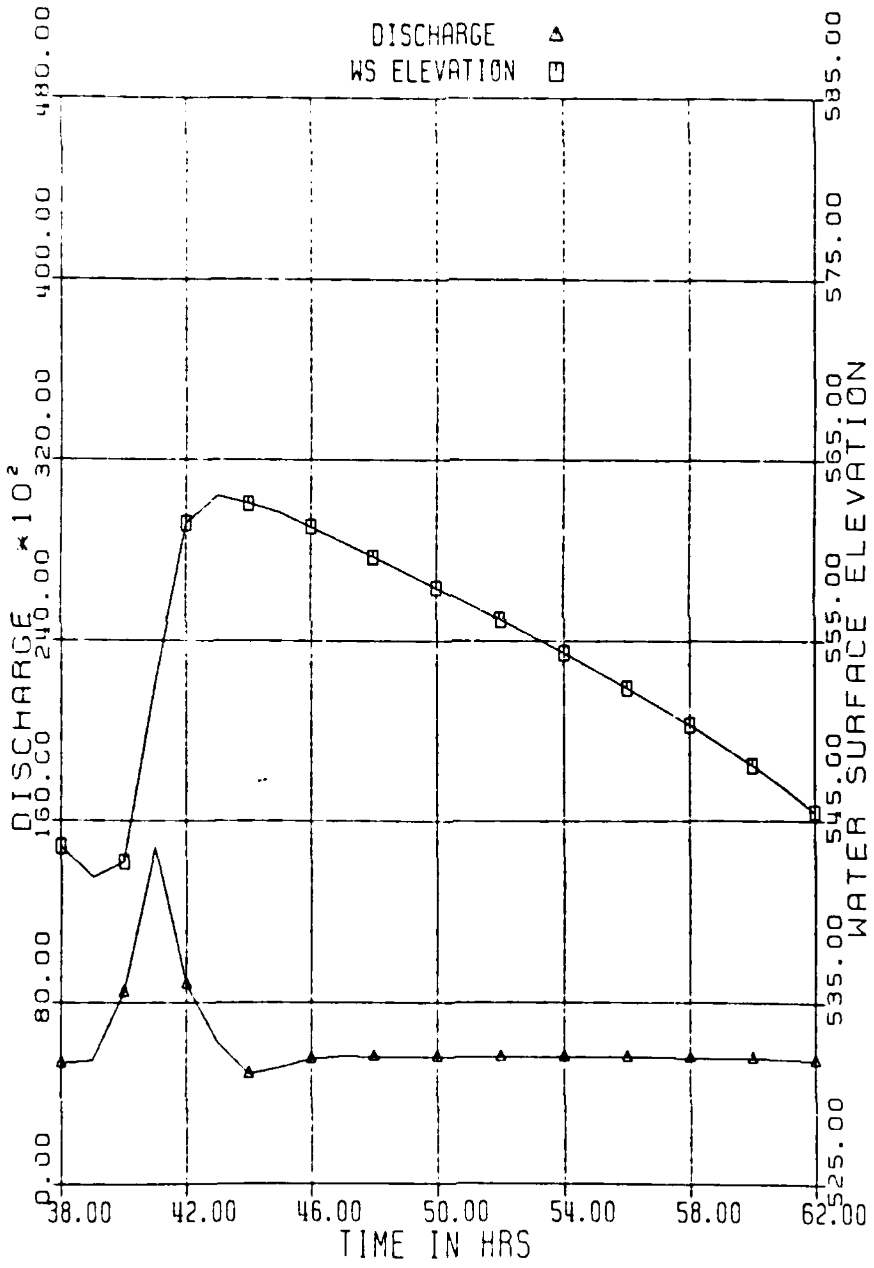
WOLF CREEK HYDROPOWER UPGRADE STUDY

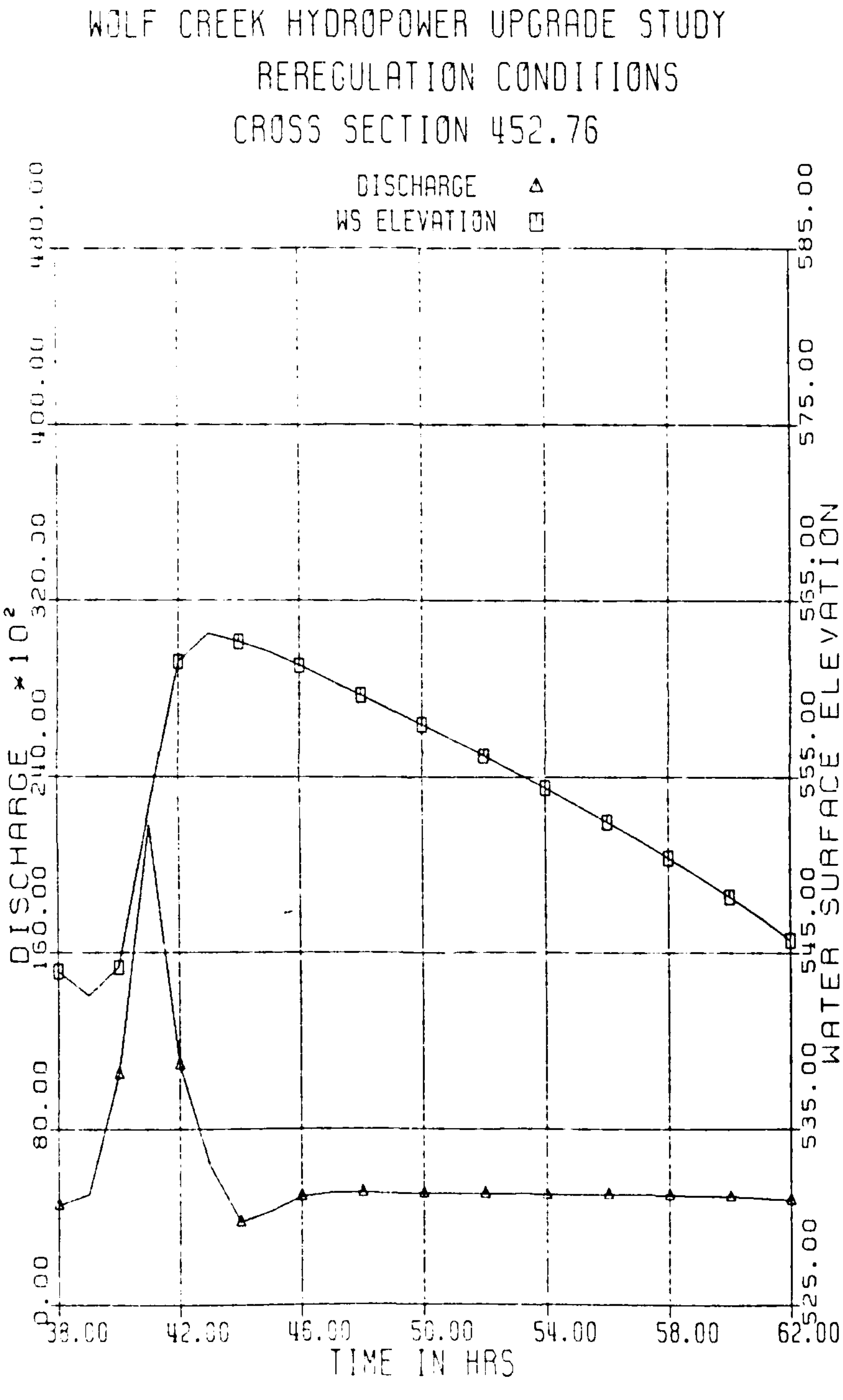
REREGULATION CONDITIONS

CROSS SECTION 451.20

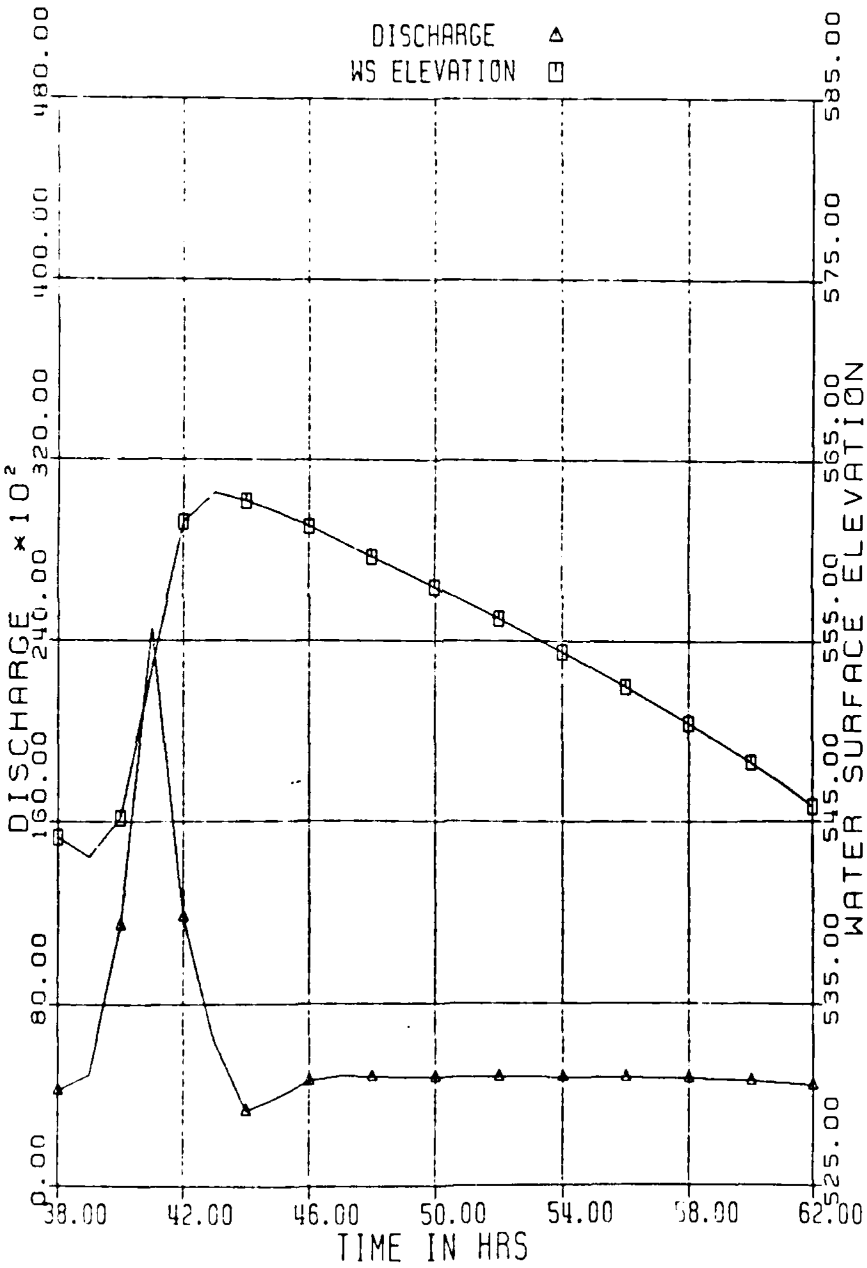


WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 451.70




WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 452.76
DISCHARGE
WS ELEVATION
DISCHARGE *10²
WATER SURFACE ELEVATION
TIME IN HRS
0.00
80.00
160.00
240.00
320.00
400.00
480.00
525.00
535.00
545.00
555.00
565.00
575.00
585.00
38.00
42.00
46.00
50.00
54.00
58.00
62.00

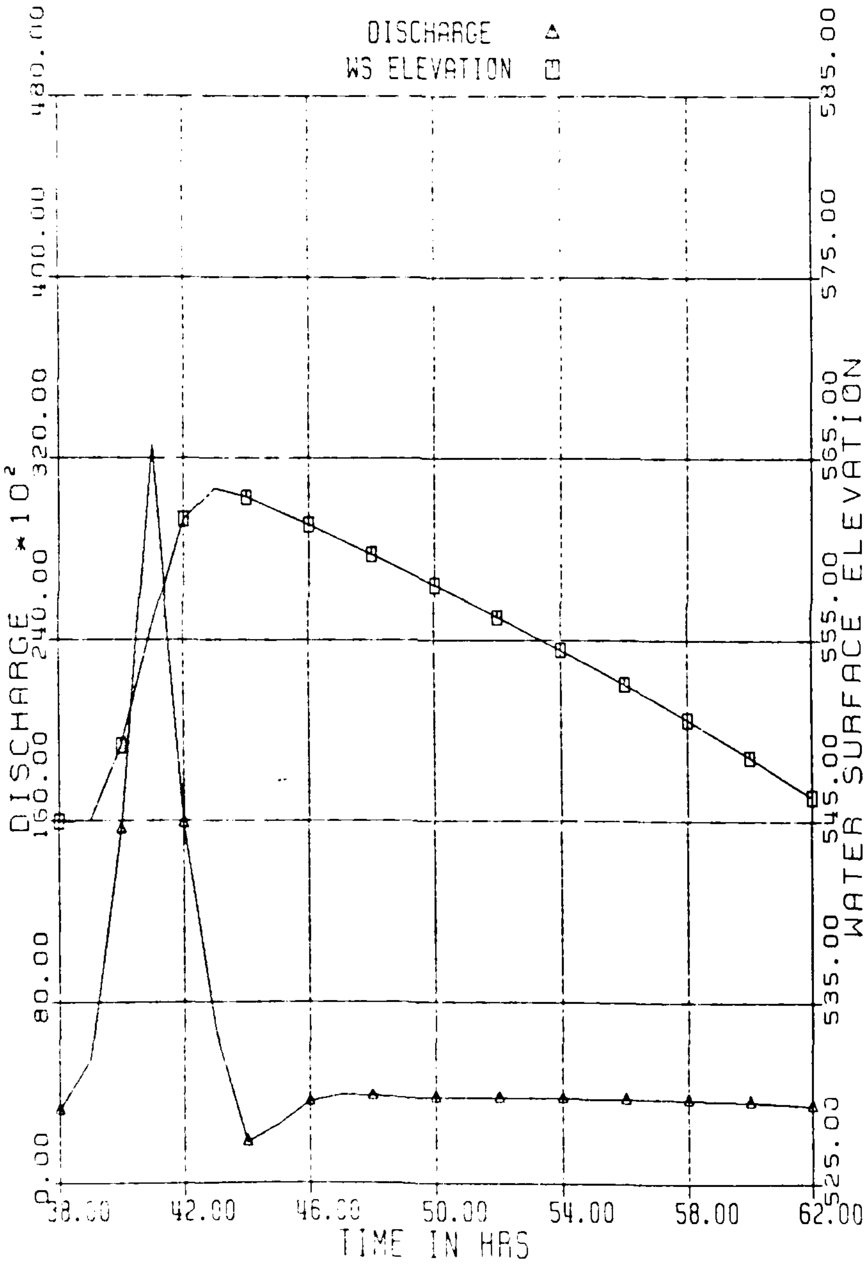
WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 453.18



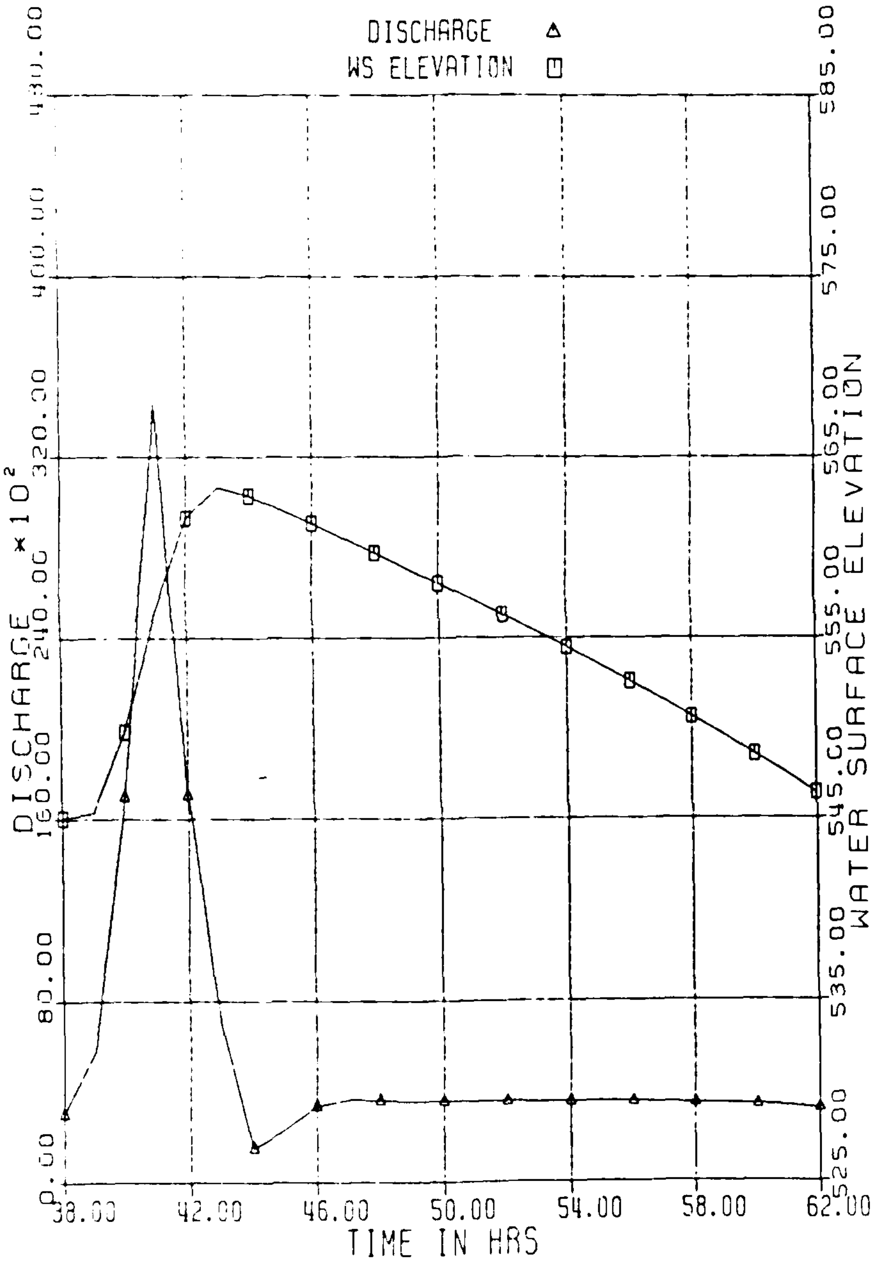
WOLF CREEK HYDROPOWER UPGRADE STUDY

REREGULATION CONDITIONS

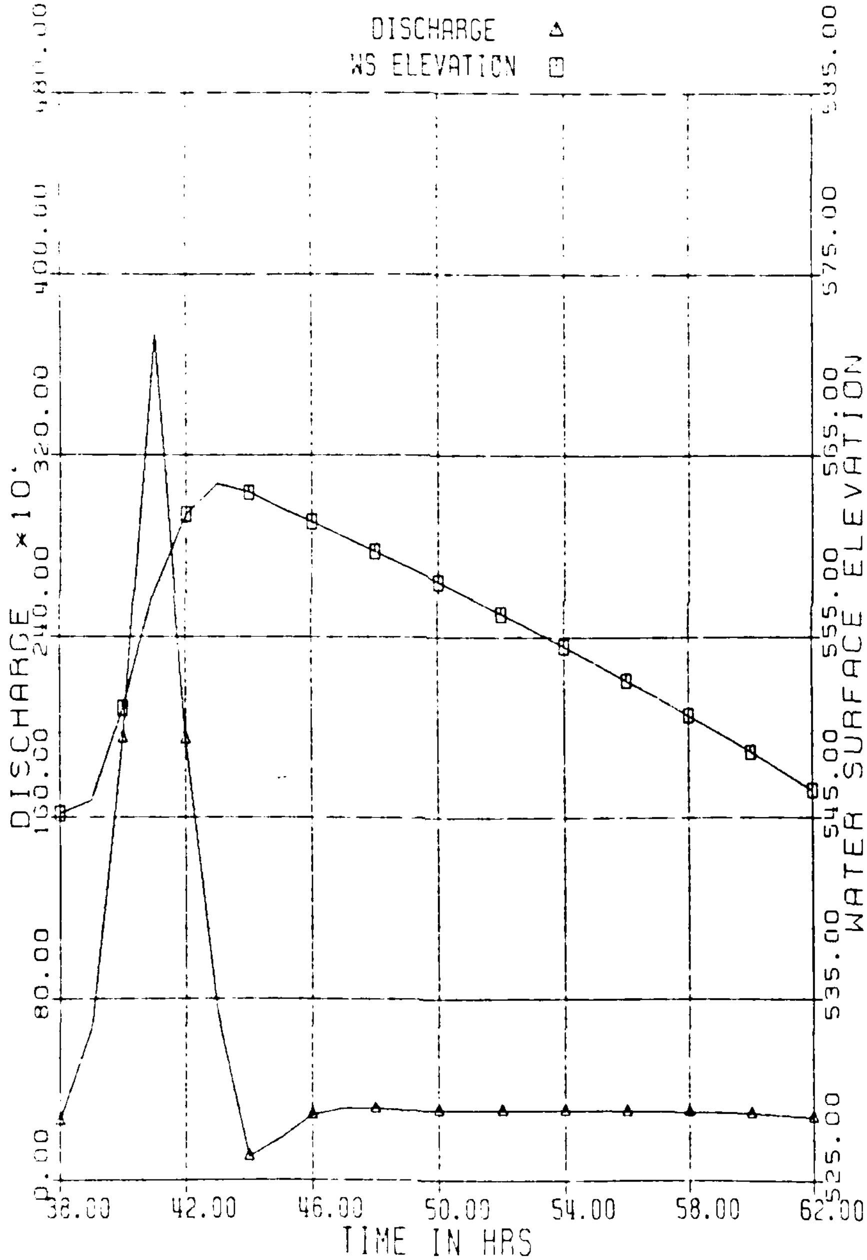
CROSS SECTION 454.70



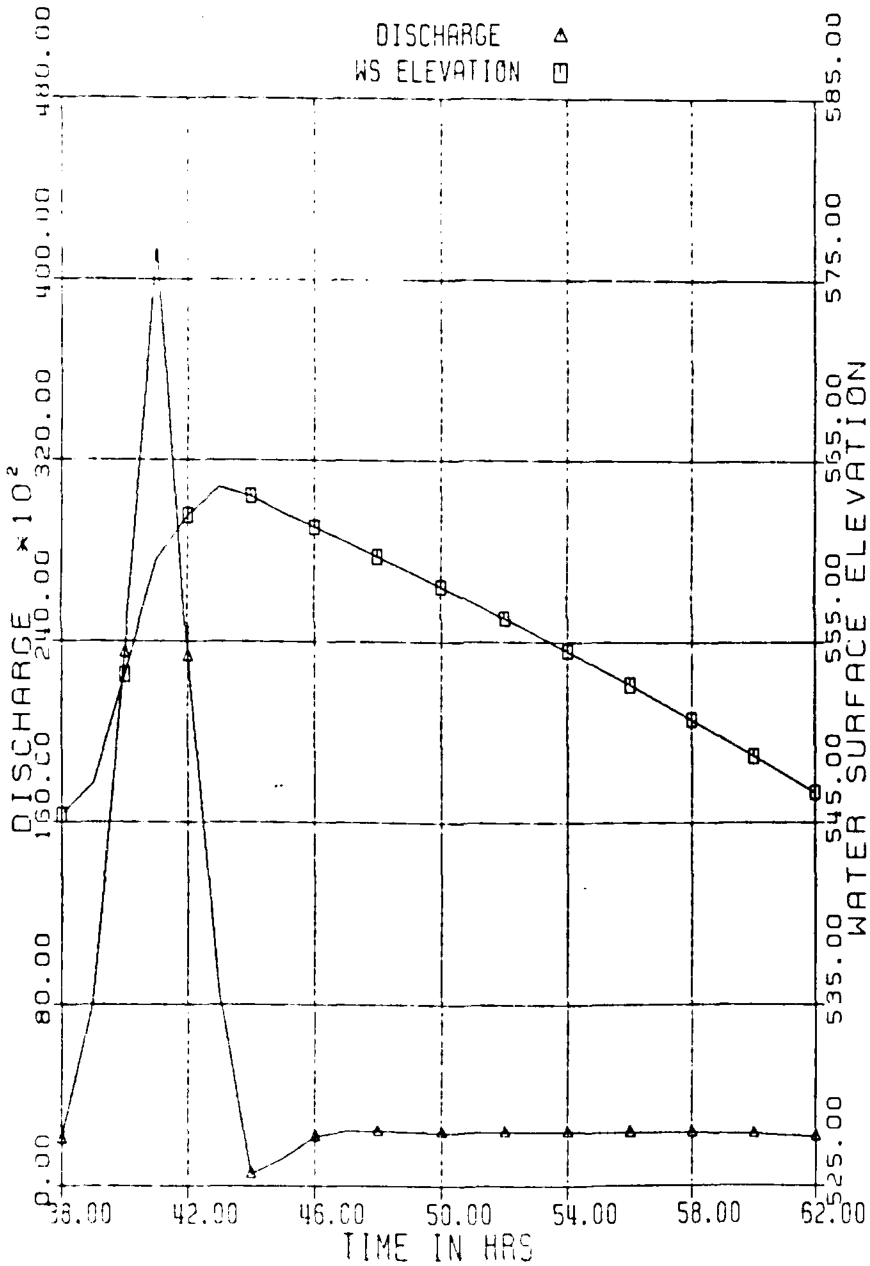
WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 455.10



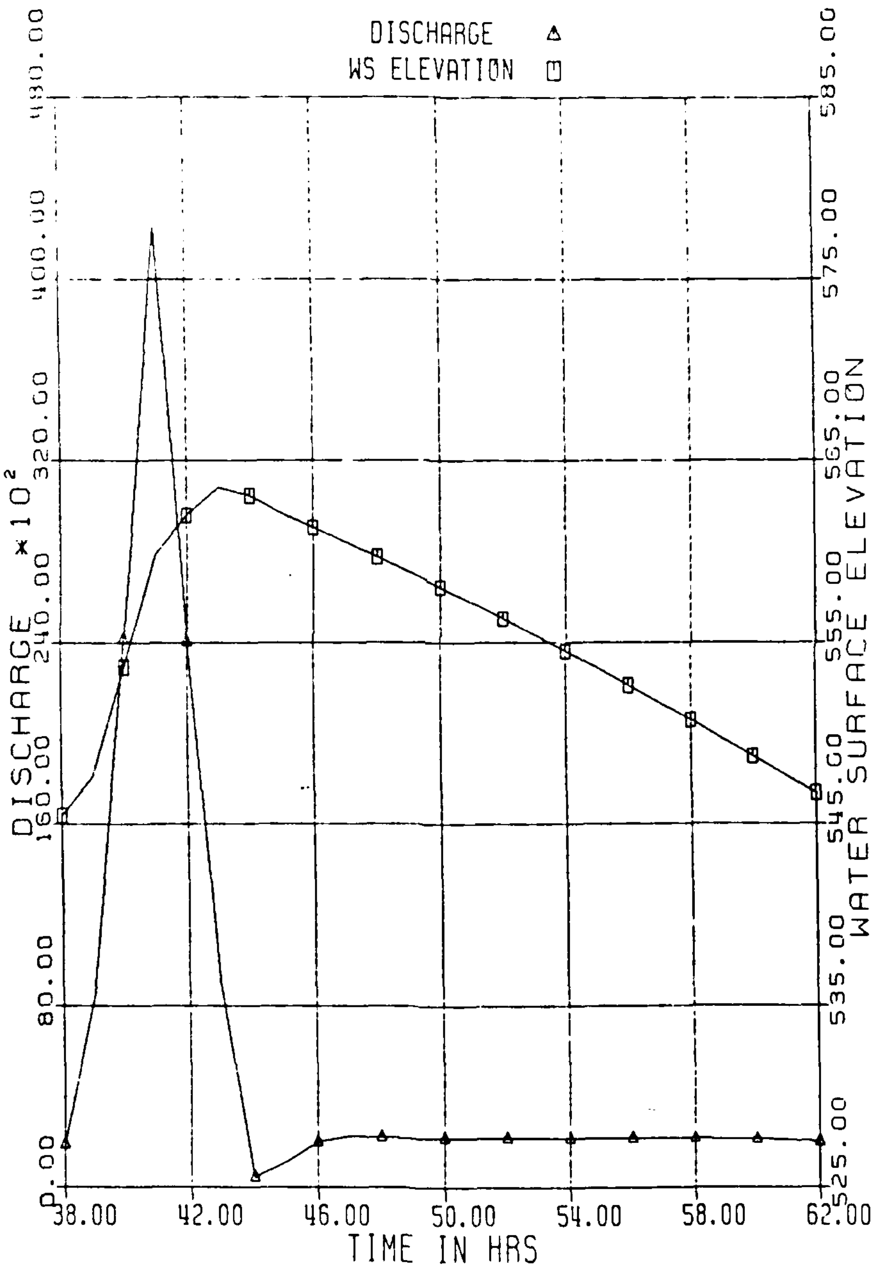
WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 455.90

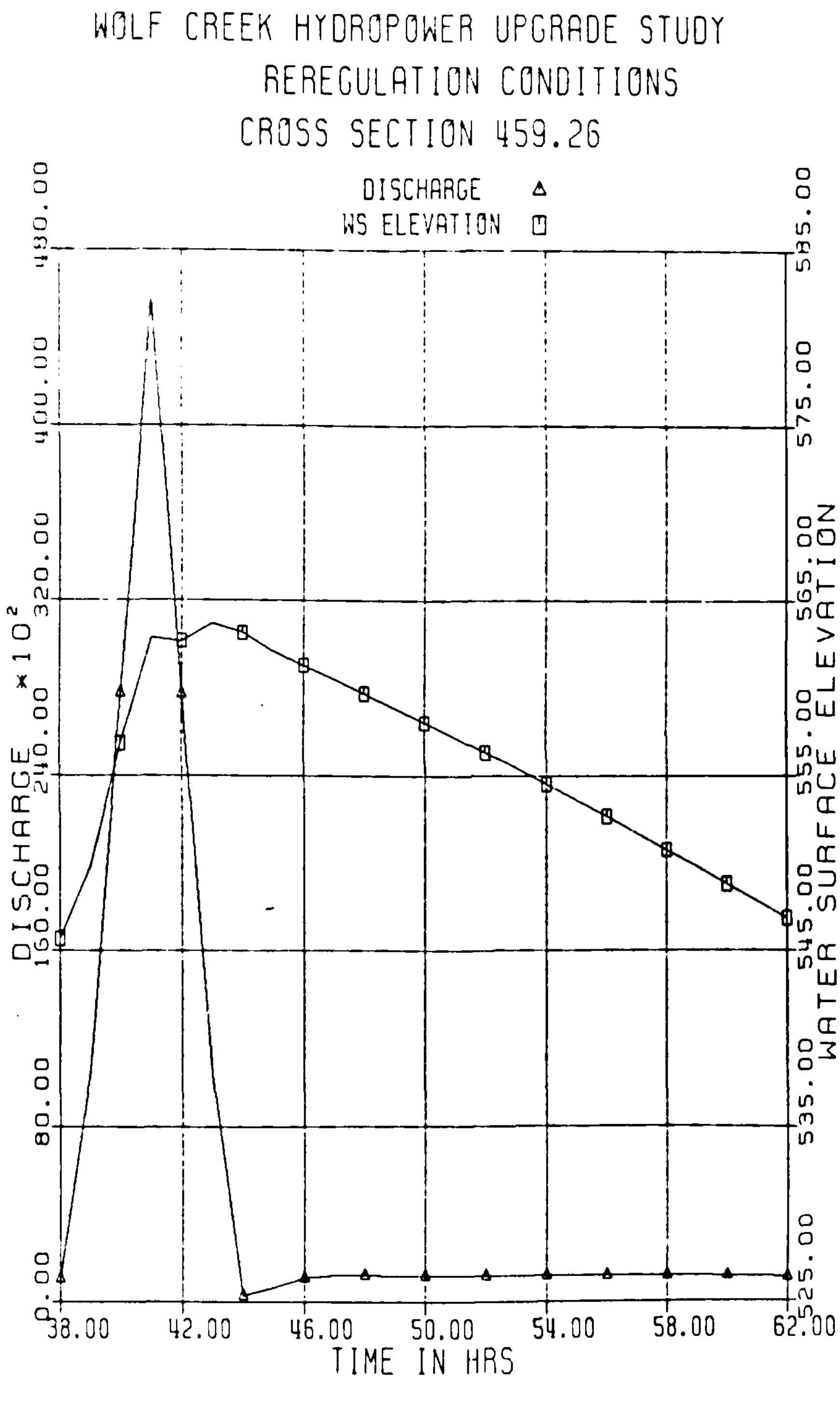


WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 457.16

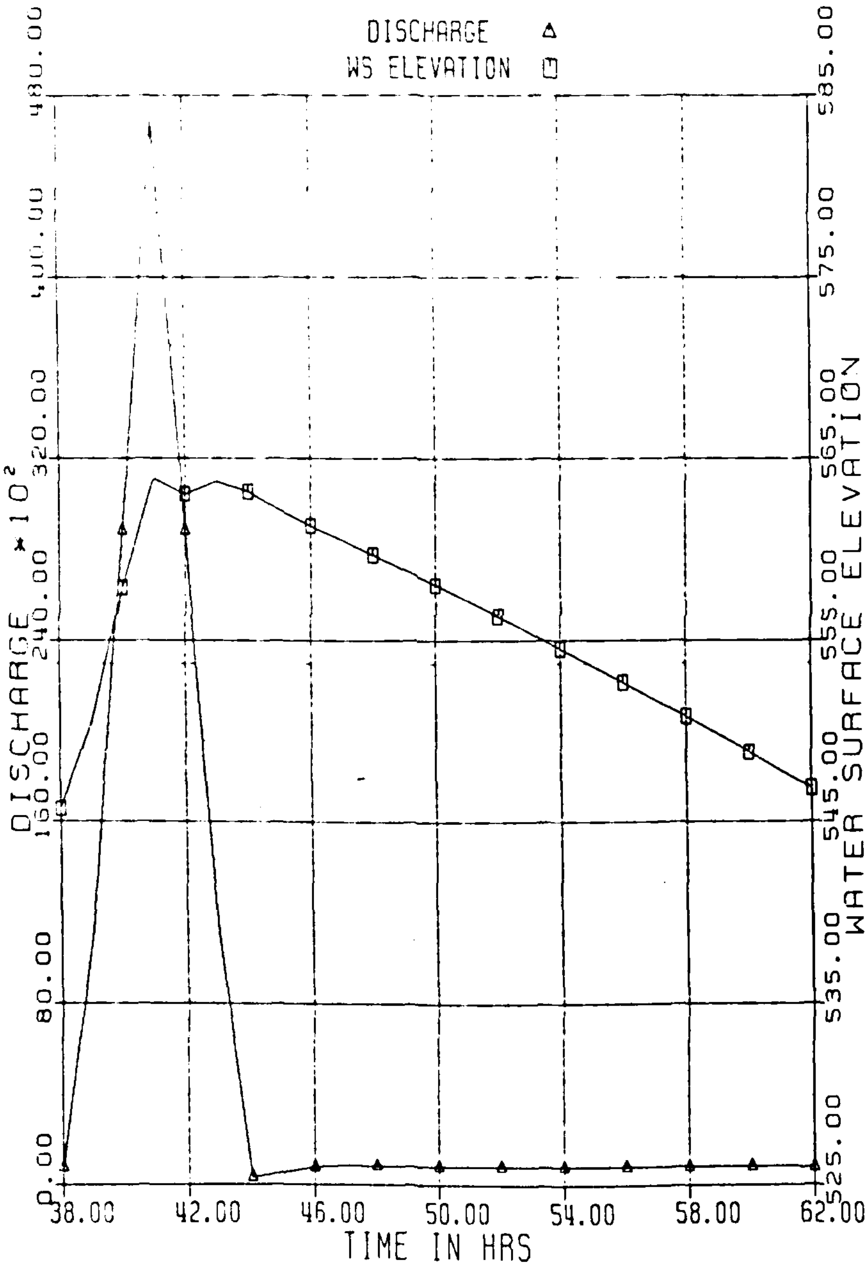


WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 457.40

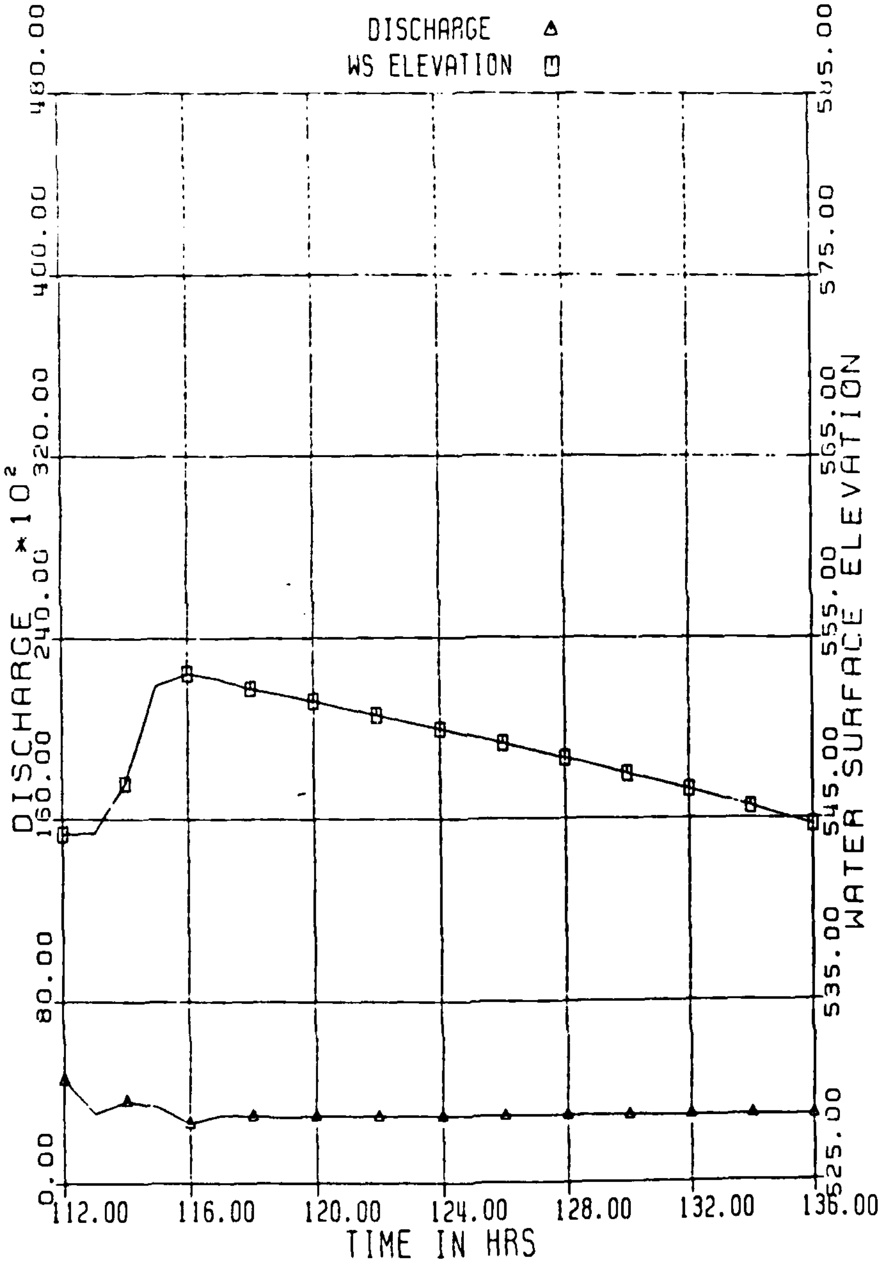



WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 459.26
DISCHARGE
WS ELEVATION
DISCHARGE ×10²
0.00
80.00
160.00
240.00
320.00
400.00
480.00
WATER SURFACE ELEVATION
525.00
535.00
545.00
555.00
565.00
575.00
585.00
38.00
42.00
46.00
50.00
54.00
58.00
62.00
TIME IN HRS

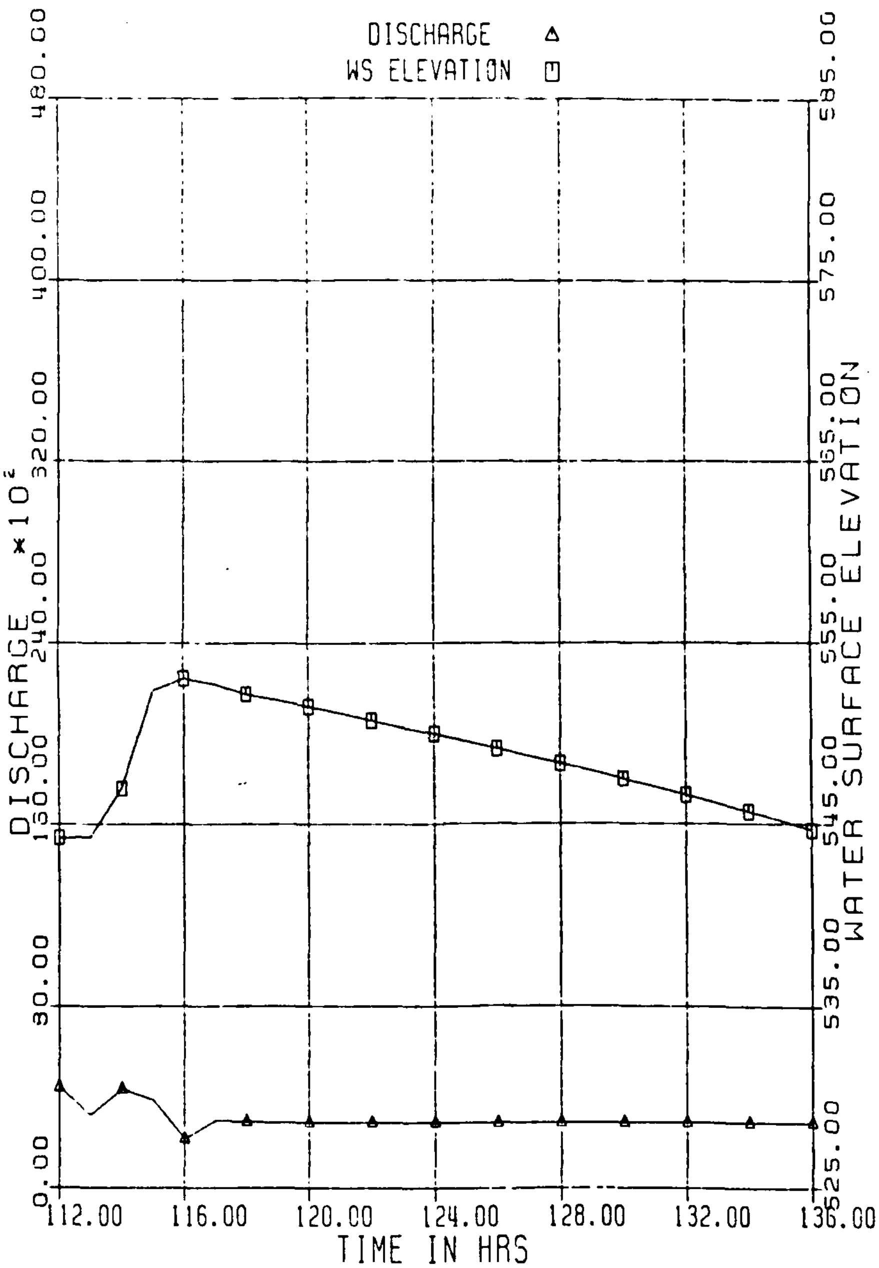
WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 460.00



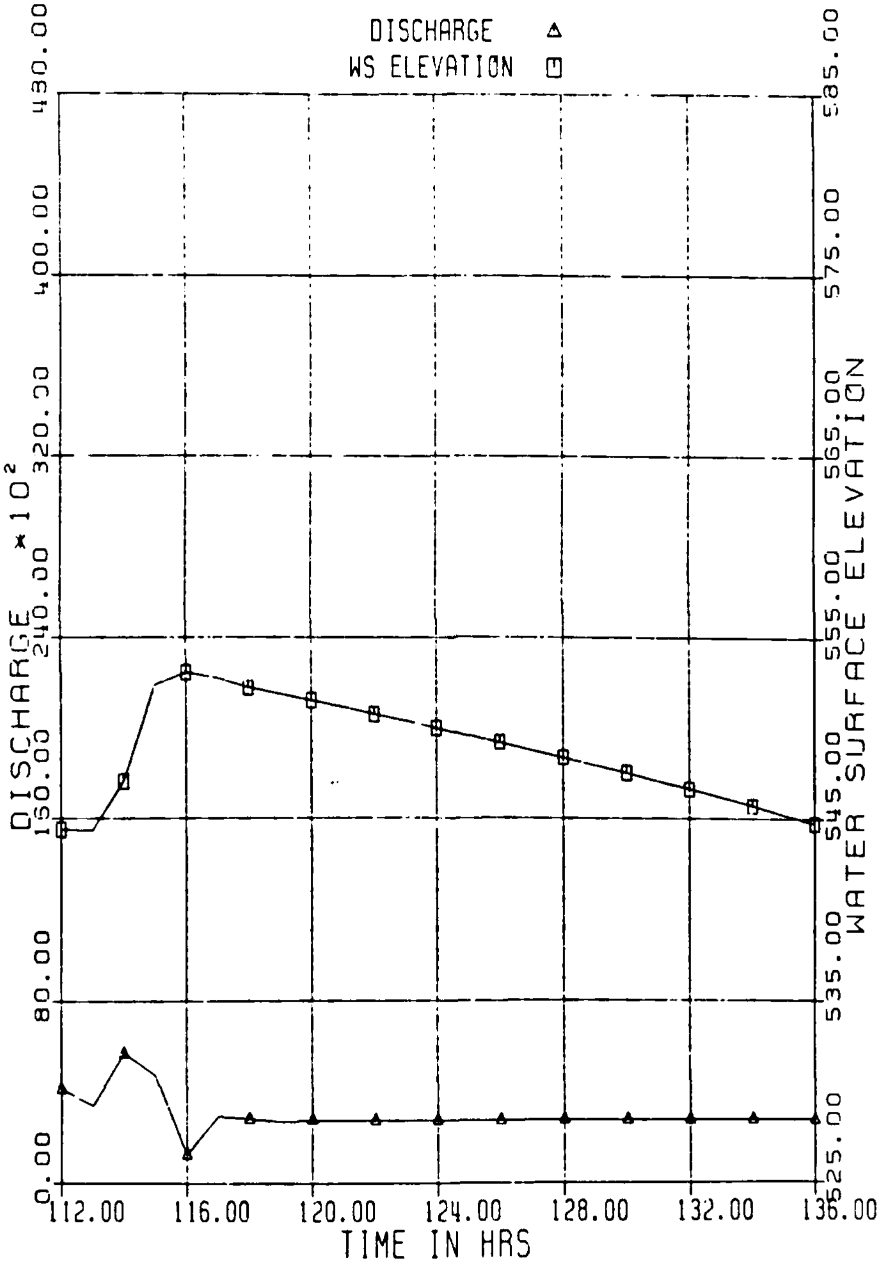
WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 450.95

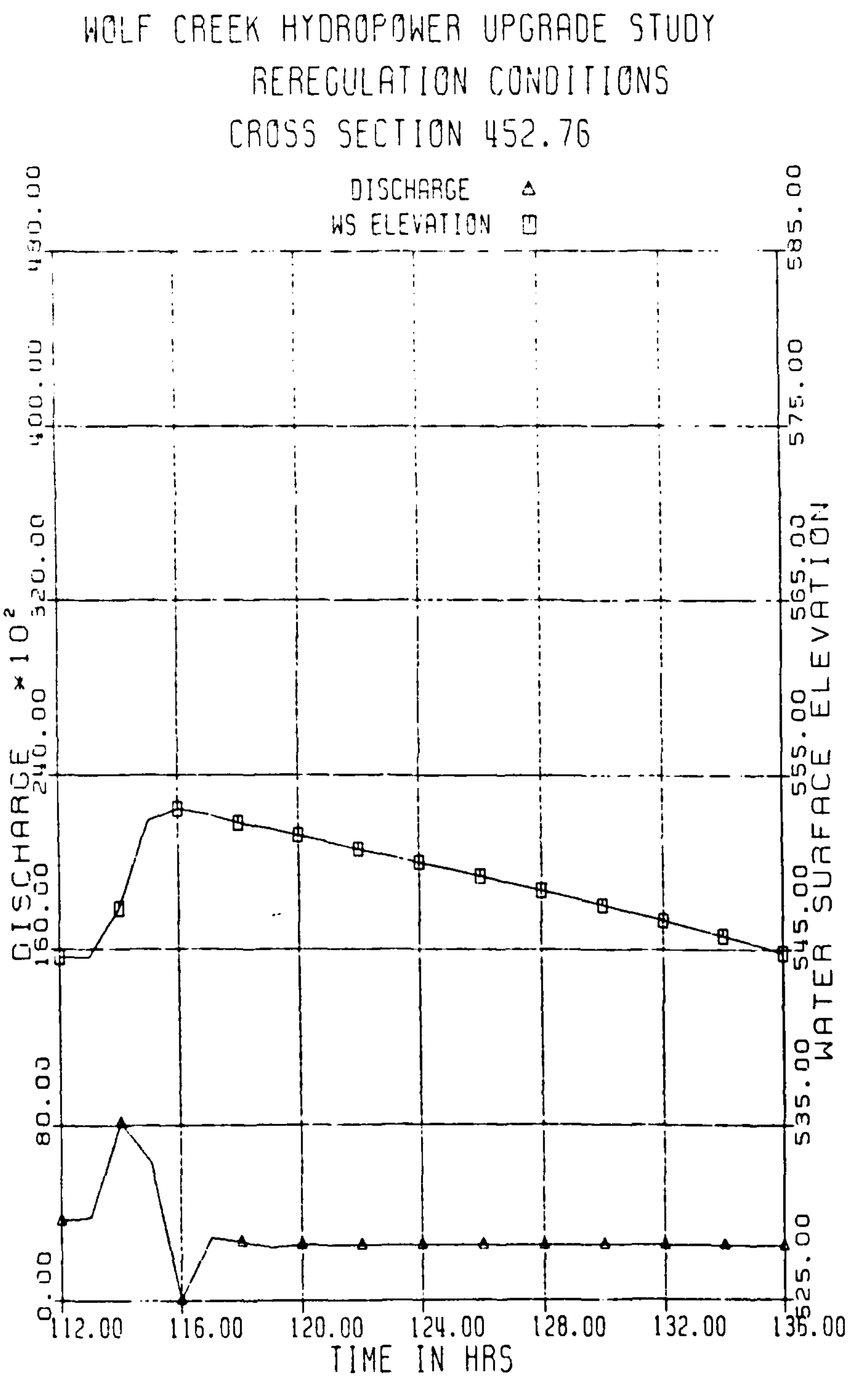


WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 451.20



WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 451.70



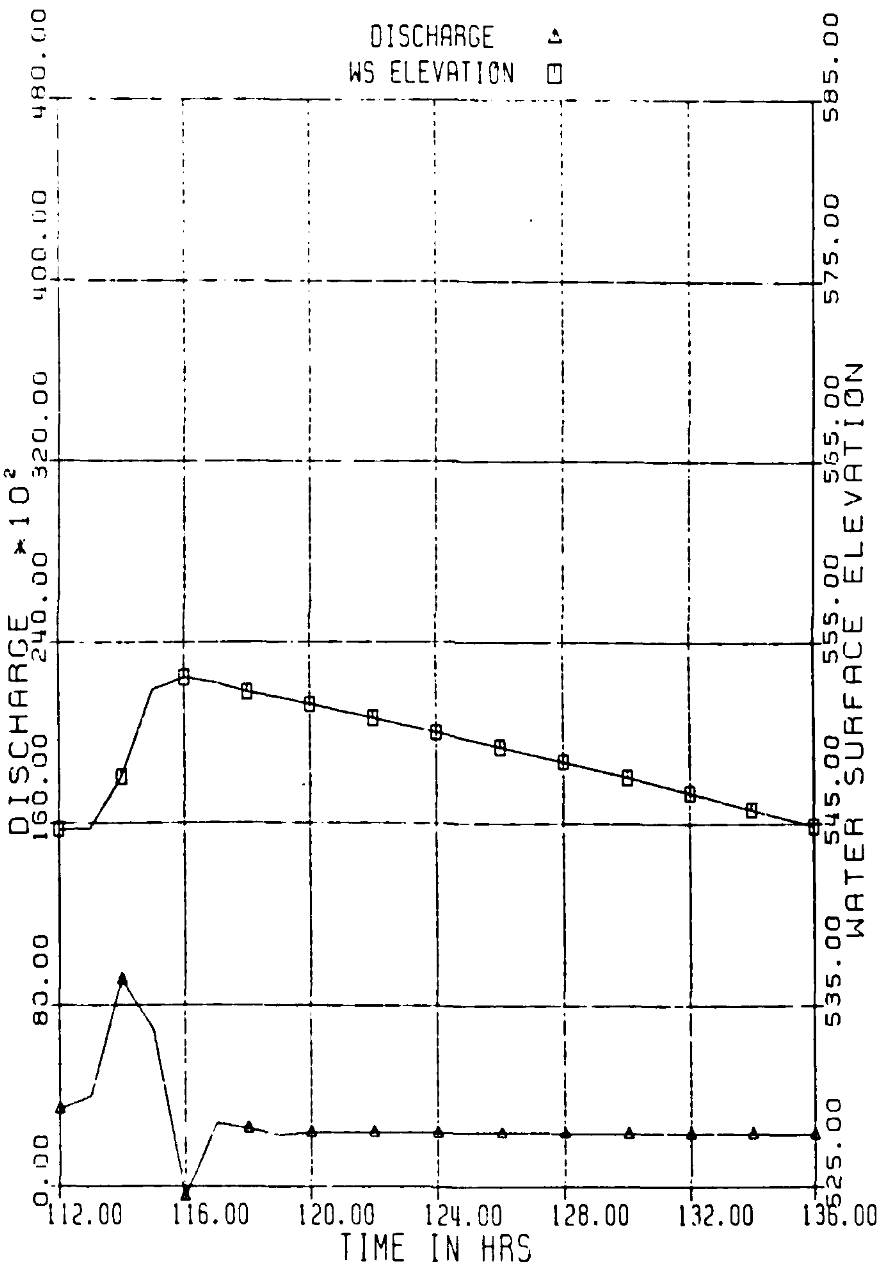


WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 452.76
DISCHARGE
WS ELEVATION
DISCHARGE ×10²
0.00
80.00
160.00
240.00
320.00
400.00
480.00
WATER SURFACE ELEVATION
525.00
535.00
545.00
555.00
565.00
575.00
585.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00
TIME IN HRS

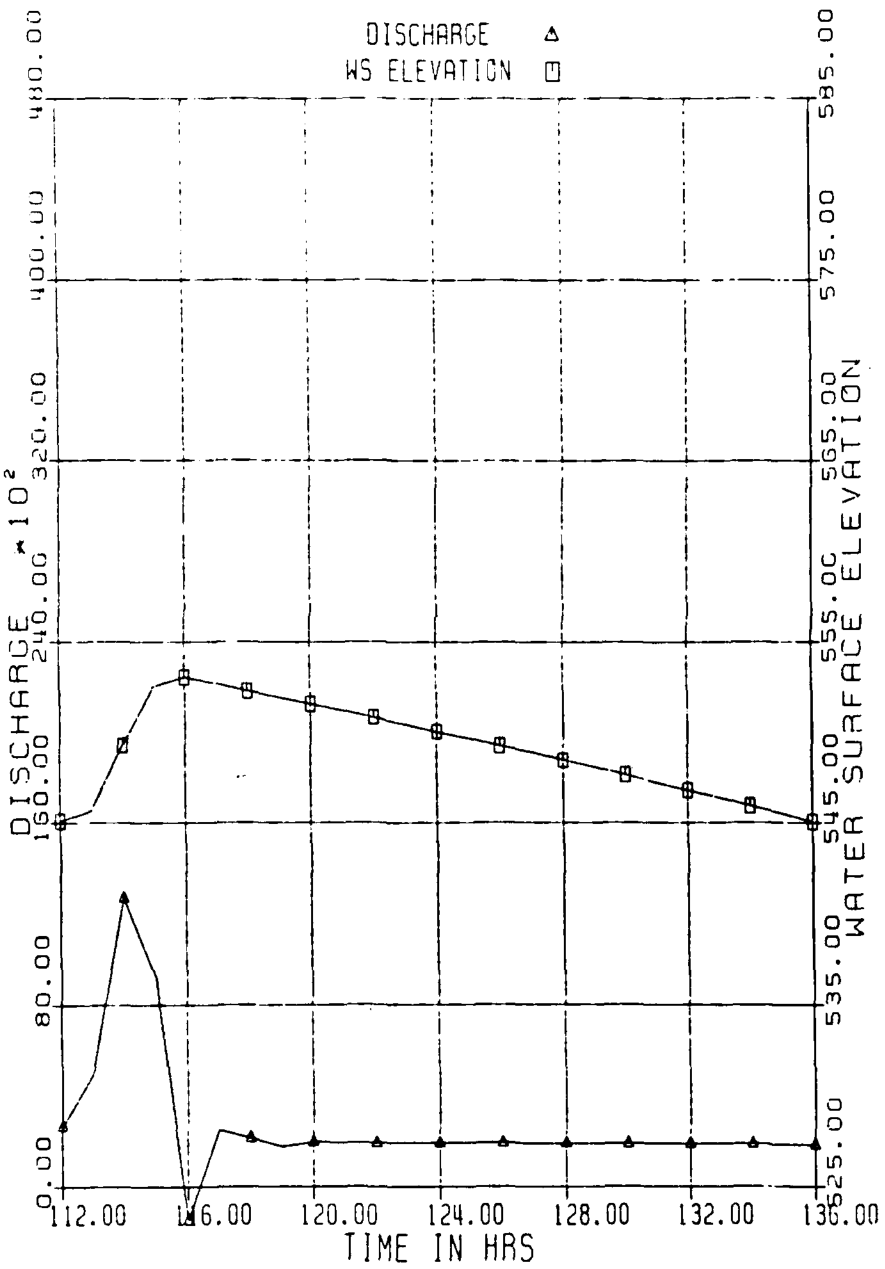
WOLF CREEK HYDROPOWER UPGRADE STUDY

REREGULATION CONDITIONS

CROSS SECTION 453.18



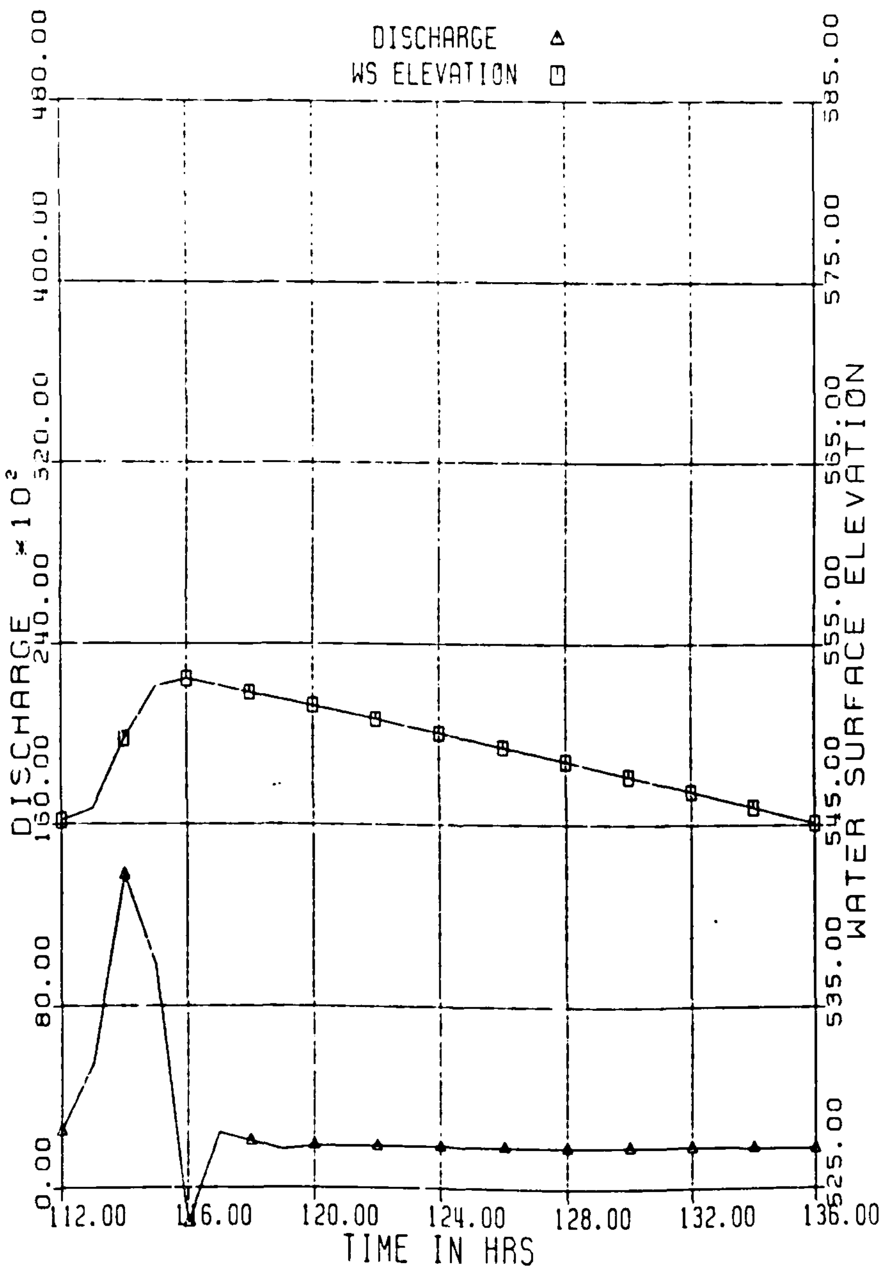
WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 454.70



WOLF CREEK HYDROPOWER UPGRADE STUDY

REREGULATION CONDITIONS

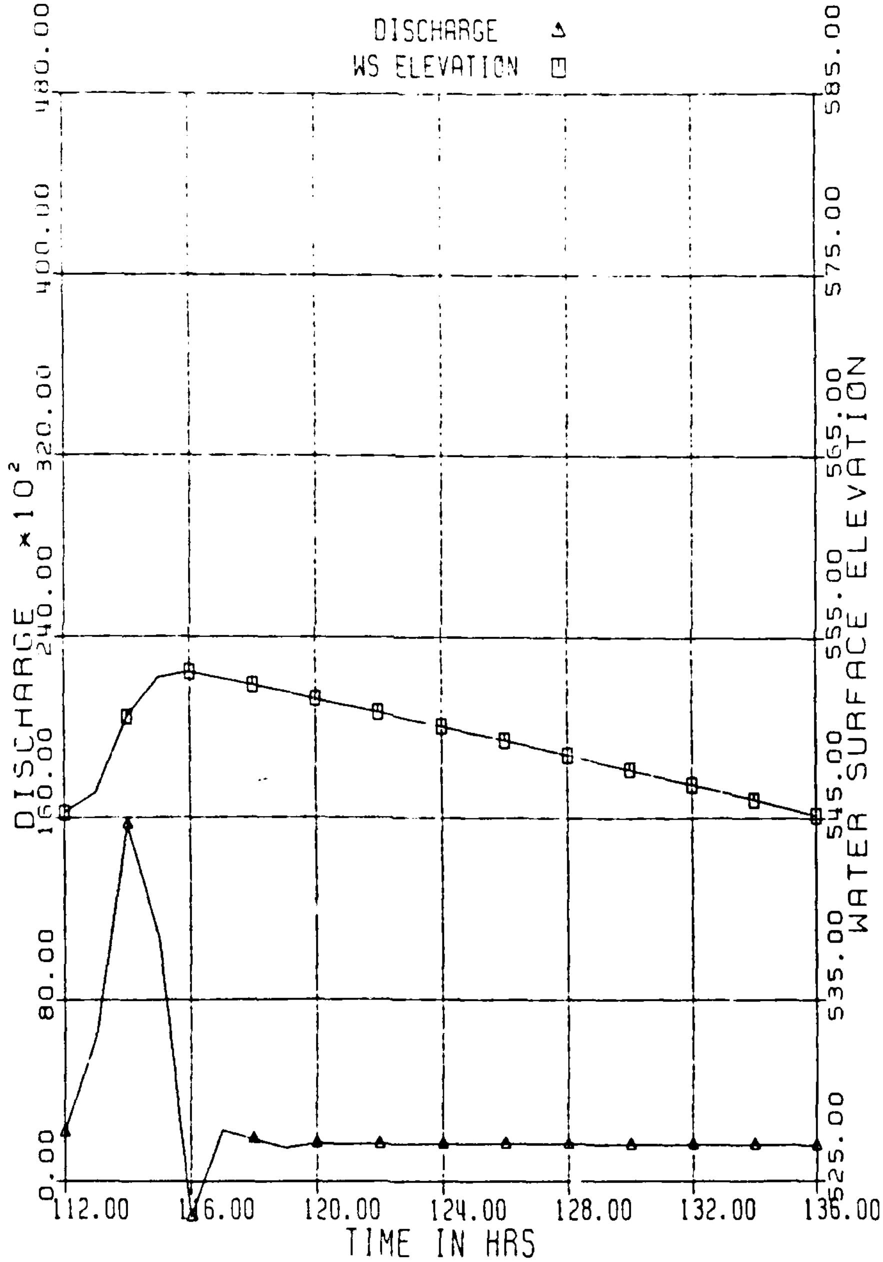
CROSS SECTION 455.10

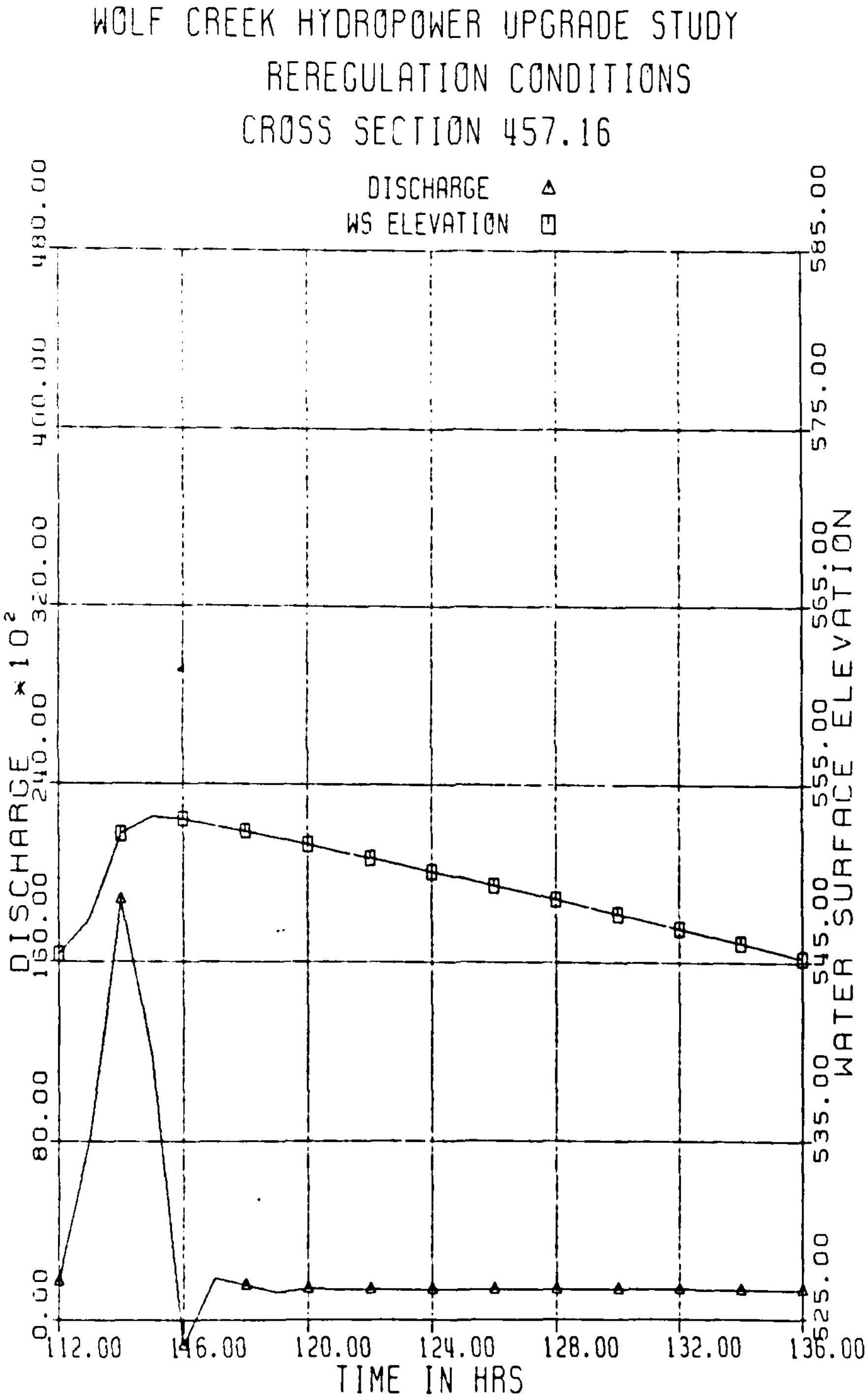


WOLF CREEK HYDROPOWER UPGRADE STUDY

REREGULATION CONDITIONS

CROSS SECTION 455.90

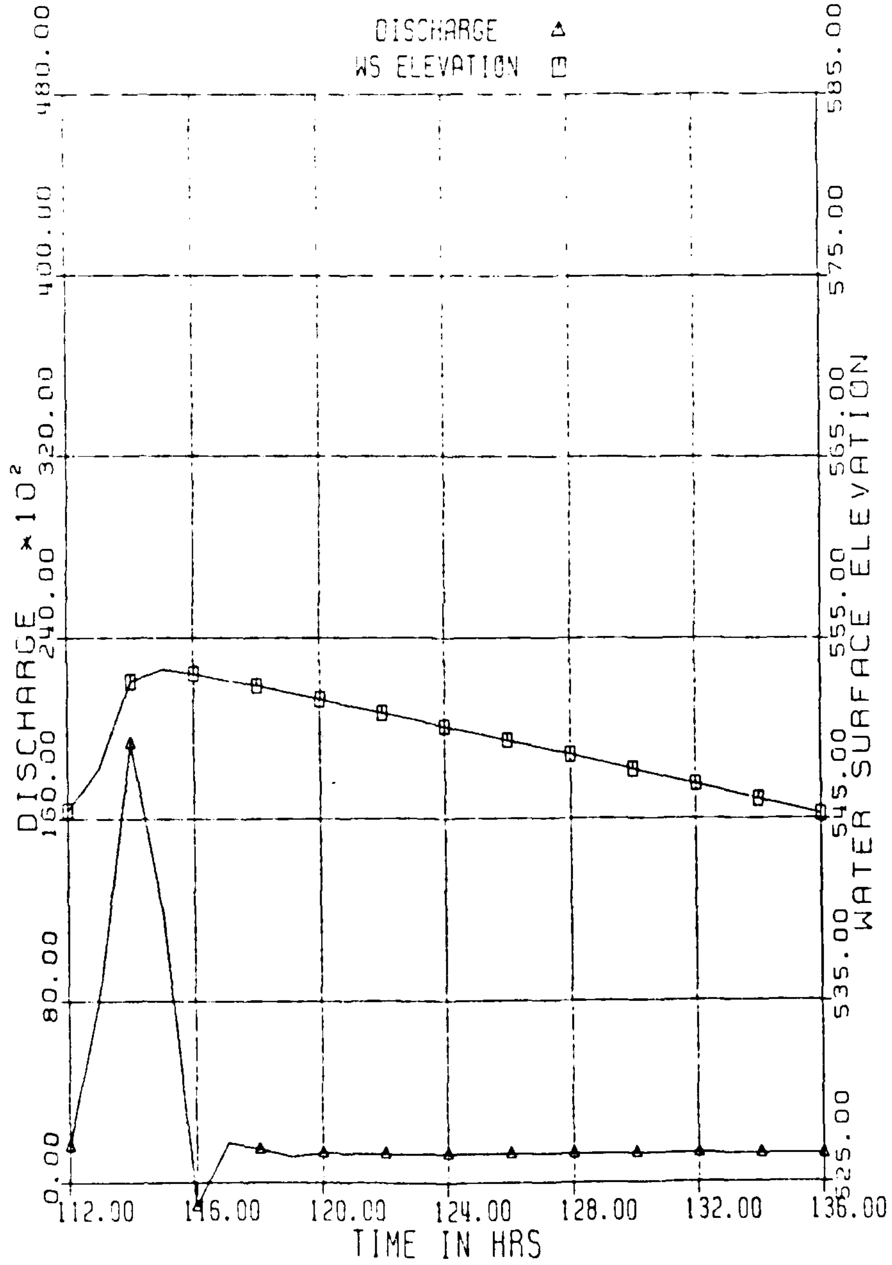



WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 457.16
DISCHARGE
WS ELEVATION
DISCHARGE $\times 10^2$
WATER SURFACE ELEVATION
TIME IN HRS
0.00
80.00
160.00
240.00
320.00
400.00
480.00
525.00
535.00
545.00
555.00
565.00
575.00
585.00
112.00
116.00
120.00
124.00
128.00
132.00
136.00

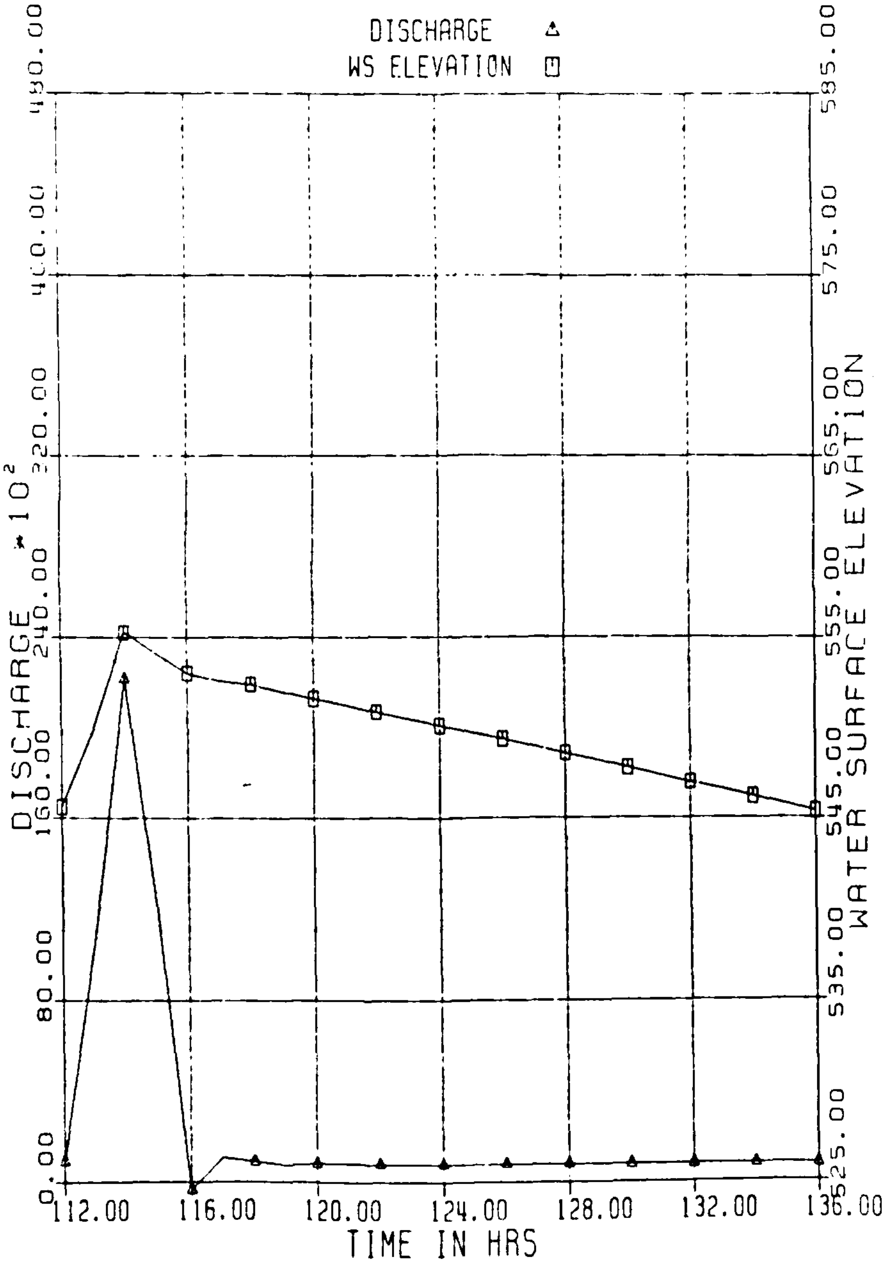
WOLF CREEK HYDROPOWER UPGRADE STUDY

REREGULATION CONDITIONS

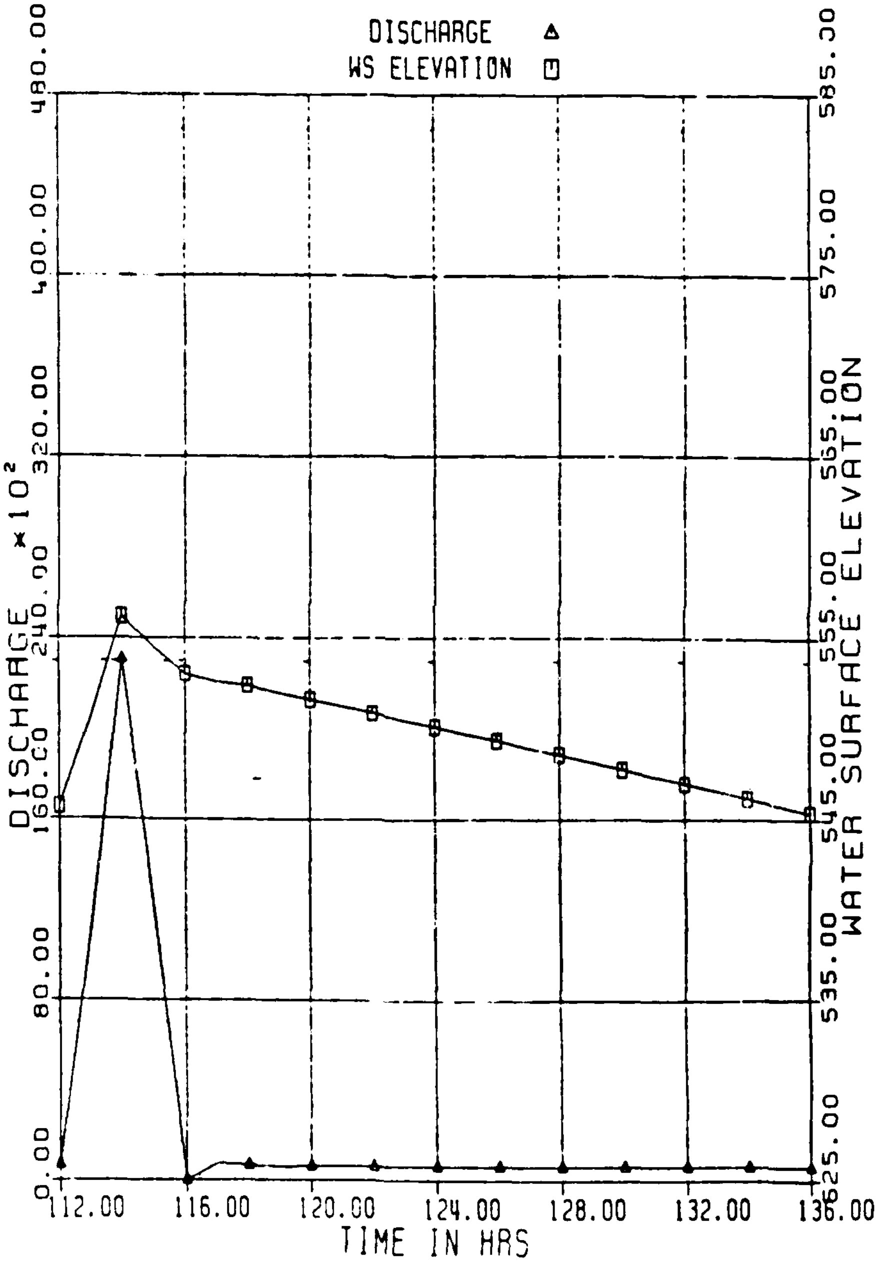
CROSS SECTION 457.40



WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 459.26



WOLF CREEK HYDROPOWER UPGRADE STUDY
REREGULATION CONDITIONS
CROSS SECTION 460.00



END

6-87

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